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EXPLORATORY DEVELOPMENT OF AIRCREW WINDBLAST PROTECTION CONCEPTS

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FOR THE COMMANDER

HENNING E. VON GIERKE
Director
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The problem of protecting aircrews from limb injuries during high-speed ejections is addressed. The problem is defined in terms of ejection experience, design requirements conflicts, and specific aircrew vulnerability to injury. Design and evaluation criteria are presented. Three arm restraint and three leg restraint concepts are described. A test and evaluation program plan is presented.

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SUMMARY

Design requirements for windblast limb protection systems to be used in current ejection seats were defined. The ACES II system was used as a baseline system. Using the baseline seat and the requirements, three arm and three leg restraint concepts were defined. A proposed program was then defined to evaluate and develop the proposed systems.

Design requirements were derived from a list of criteria or constraints for the system as defined in the reference to the escape, aircraft, crew flight conditions and using commands' needs. Resulting requirements were then rank ordered and significant interactions between them identified. Identification of negative interactions highlights the significant trades necessary to design a successful windblast protection system.

Ejection events and the resulting environment the crew is exposed to were then analyzed to define the physical actions the men and system must contend with. Review of previous ejection injuries and limb restraint systems was included to further refine the understanding of injury mechanisms. Specific injury mechanisms of the knees, shoulder, elbow, and spinal column are presented.

Using the requirements and injury mechanisms the six candidate protection systems were defined. A proposed program for concept refinement and final selection is presented.

PREFACE

This report was prepared in partial fulfillment of Contract No. F33516-78-C-0514. The research was accomplished by Rockwell International, Los Angeles Division, 815 Lapham St., El Segundo, California 90009. Frank E. Drsata was the Program Manager and R. J. Cummings was the Principal Investigator.

The Air Force Technical Monitor was James R. Brinkley of the Biomechanical Protection Branch, Biodynamics and Bioengineering Division of the Aerospace Medical Research Laboratory.

This research was conducted to provide data on design requirements, constraints, and criteria for a windblast protection system for open ejection seats and to develop and select candidate protection concepts for further study.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

LIST OF ILLUSTRATIONS

LIST OF TABLES

INTRODUCTION

PROBLEM DEFINITION

In high-speed open-seat ejections, aerodynamic and inertial forces can injure the unrestrained limbs of the seat occupant. The problem is how to develop a limb restraint design which will safely restrain the limbs against the action of these forces while conforming to design constraints which arise from aircraft and escape system requirements; from human vulnerabilities to injury; from expectations of the users regarding encumberances, comfort and appearance; and from expectations of the support commands regarding reliability, maintainability, logistics, cost and schedule.

PROBLEM CONTEXT

Historical

Studies of ejection incidents have shown that injuries to the limbs are the most significant factor governing the rate of safe recovery from high-speed ejections (References 1 through 5). The estimated incidence of limb injuries in the absence of restraints ranges from about 20 percent at 400 KEAS to nearly 100 percent at 600 KEAS. In combat situations, limb injuries greatly reduce the chance of rescue from behind enemy lines and increase the risk involved in rescue operations. Many attempts have been made at designing limb restraint systems for open-ejection seats. The primary reasons why these designs are not acceptable for use in new fighter aircraft are as follows:

1. Excessive weight and/or bulk.

2. Users judge them excessively encumbering or unreliable.

3. The designs have proved to be ineffective or have introduced new injury mechanisms.

Aircraft Performance Requirements

The missions for new fighter aircraft demand higher velocities and maneuvering accelerations, and lower altitudes. The demand for higher velocities shifts the expected ejection-speed frequency distribution toward higher ejection velocities and increases the expected number of ejections in the dynamic pressure region where limb injuries are probable. Demands for higher velocities also creates demand for reduced cross section and, therefore, less bulk. Demand for higher maneuvering accelerations creates demand for reduced gross weight. Demand for operation at lower altitudes

creates demand for better low altitude recovery performance from escape systems.

Escape System Performance Requirements

Mission performance requirements for open-seat escape systems are driven by the improving low-altitude high-speed performance of military aircraft. To improve low altitude recovery performance, the delay between system initiation and catapult ignition has been shortened to only that required to achieve canopy divestment. Delay for canopy divestment may be as short as 120 milliseconds. The divestible part of some new cockpit canopies, for example the F-16, is continuous down to the fuselage outer mold line. In such aircraft, the seat-occupant is exposed to windblast immediately after the canopy is unlatched. Therefore, if limb restraint must occur concurrently with divestment, the limb restraint system must deploy very rapidly while exposed to windblast.

Ejection Seat State-of-the-Art

In the region of high dynamic pressure where limb injuries are probable, and during the period between seat-rail separation and the beginning of stabilized deceleration on the drogue chute, a light weight, standard shaped ejection seat will usually show angle-of-attack instability (References 6 through 9). As a result, the direction and magnitude of the aerodynamic and inertial forces acting on the limbs, body and seat may change rapidly during this period. Also the seat can have a large angle-of-attack by the time the drogue chute inflates. When this occurs, the seat shows large changes in translational and angular acceleration which may result in violent movement between the seat and occupant. After drogue stabilization, the seat can show high roll rates which the drogue may not control. When this occurs, seat-man separation can be unstable and result in an off-angle extraction of the occupant from the seat.

General

Contemporary Air Force ejection seats use either center-pull or side-arm initiators. Therefore, the limb restraints should be designed for both initiator types. The need for a workable limb restraint system is immediate. Therefore, the limb restraint design should be compatible with the goal of rapid development, evaluation and implementation. The maximum loads which a limb restraint system will have to react are not precisely known due to difficulties of extrapolating windtunnel research data to the actual dynamic conditions of a high-speed ejection. Therefore, the proposed restraint design should provide a wide margin of safety in its maximum load parameters.

STRATEGY FOR PROBLEM RESOLUTION

This attempt to solve the limb restraint design problem began with a review of the scientific literature related, in general, to human interactions with open-seat ejection systems, and in particular, to the mechanics of windblast induced limb injuries. During this review, particular attention was paid to those characteristics of previous limb restraint design solutions which seemed to be the cause of those solutions, unacceptability for use on the ejection seats of new military aircraft.

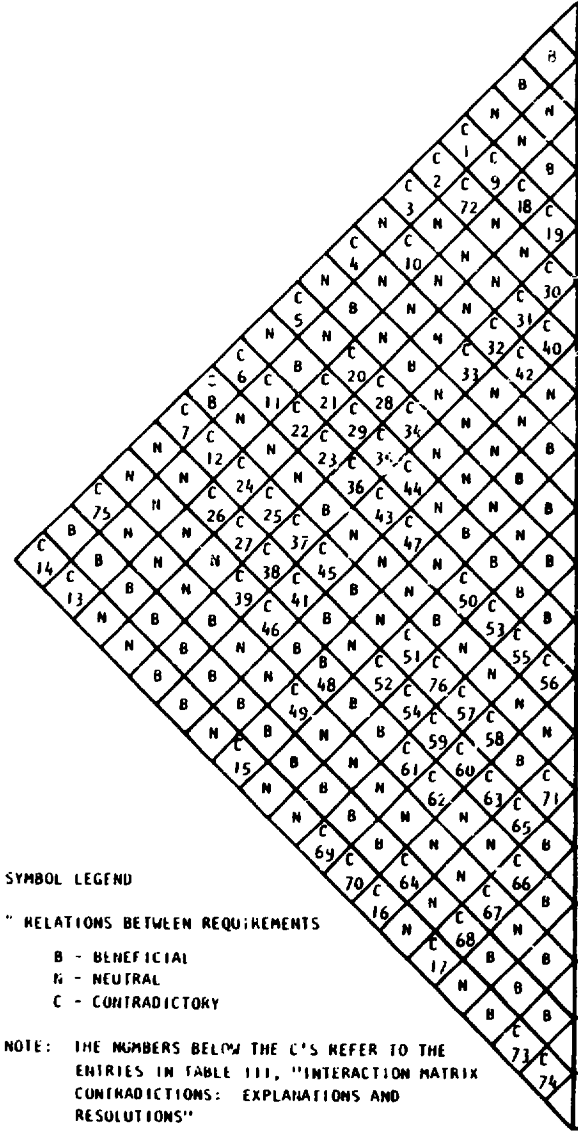
Subsequent to the literature review, an analysis was conducted on the requirements for an acceptable limb restraint design. One aim of this analysis was to identify and assess contradictory interactions between independent design requirements. A contradictory interaction is indicated when it can be shown that a design feature which improves performance against one requirement, degrades performance against another. As a means for systematically searching for such interactions, a list of independent design requirements was compiled and then crossed with itself to form a matrix. Each cell of this matrix represents the potential interaction between a pair of requirements as shown in Table 1. Each of the paired requirements was subjectively assessed for any significant interaction, and the corresponding matrix cells were marked to indicate the nature of the interaction as either beneficial, neutral or contradictory. A list of the contradictory interactions was made. The list which gives a brief explanation of each interaction, and possible approaches to resolution, is presented in Table 2. Of the 180 potential interactions defined by the requirements matrix, 76 contradictory interactions were identified. This large number of conflicts between requirements implies that any windblast protection concept will necessarily represent a large set of trade-offs between requirements, and that no concept can fully meet all of the design requirements. Since each contradictory interaction between requirements represents a potential trade-off situation, there is a need for organizing these interactions according to their relative importance so that the acceptability of the trade-offs inherent in a design concept may be judged. Since the importance of each interaction is related to the importance of the two requirements involved, the design requirements first were ranked according to their relative importance on the basis of their contributions to the following goals:

First, successful completion of the military mission

Second, safe recovery of the seat occupant

Third, satisfaction of the functional and psychological needs of the occupant

Table 1. PRESENTATION OF DESIGN REQUIREMENT INTERACTIONS IN A MATRIX FORMAT



1. CREW SIZE - ACCOMMODATE AND BE FUNCTIONALLY INSENSITIVE TO ALL VARIABILITY IN CREW SIZE
2. PERSONAL EQUIPMENT - ACCOMMODATE AND BE FUNCTIONALLY INSENSITIVE TO ANY PERSONAL EQUIPMENT LIKELY TO BE WORN BY THE EJECTION SEAT OCCUPANT
3. REACH - PRESERVE THE REACH ACCESSIBILITY OF CONTROLS AND EQUIPMENT INTENDED FOR USE BY THE SEAT OCCUPANT
4. VISION - PRESERVE THE INTERNAL AND EXTERNAL VISIBILITY ENJOYED BY THE SEAT OCCUPANT
5. DESIGN TO COST/LIFE CYCLE COST - KEEP DEVELOPMENT AND LIFE CYCLE COSTS TO MINIMUM LEVEL CONSISTENT WITH ACHIEVEMENT OF MISSION OBJECTIVES
6. WEIGHT - KEEP WEIGHT TO MINIMUM LEVEL CONSISTENT WITH ACHIEVEMENT OF MISSION OBJECTIVES
7. SEAT STABILITY - PRESERVE OR IMPROVE THE AERODYNAMIC STABILITY OF THE SEAT
8. SEAT SEPARATION - PROVIDE POSITIVE FAIL-SAFE RELEASE OF ANY ACTIVE RESTRAINTS AT THE SAME TIME AS PRIMARY RESTRAINT RELEASE
9. MANUAL RELEASE ACCESSIBILITY - PRESERVE THE SEAT OCCUPANT'S ACCESS TO THE MANUAL RESTRAINT RELEASE HANDLE
10. LANDING ENTANGLEMENT AVOIDANCE - AVOID NETS OR STRAPS WHICH MIGHT ENTANGLE AN EJECTEE'S LIMBS DURING LANDING
11. INGRESS/DONNING - AVOID COMPLICATION OF THE INGRESS PROCEDURE AND ADDITION OF EXTRA ATTACHMENT TASKS
12. EGRESS (EMERGENCY)/DOFFING - INTEGRATE ANY RESTRAINTS WITH THE PRIMARY RESTRAINT SINGLE POINT RELEASE AND AVOID EXTRA DOFFING TASKS
13. DRAG AND INERTIAL FORCES - APPLY FORCES TO, OR SHIELD, THE HEAD AND LIMBS TO PREVENT HAZARDOUS RELATIVE MOVEMENT BETWEEN THESE AND THE TORSO
14. LOAD DISTRIBUTION - LET THE PRIMARY RESTRAINT SYSTEM CARRY THE MAJOR LOADS DUE TO DECELERATION BETWEEN THE SEAT AND TORSO
15. PRE-EJECTION POSITIONING - AVOID SENSITIVITY TO THE PRE-EJECTION POSITION OF THE BODY AND LIMBS BY AUTOMATICALLY POSITIONING THEM BEFORE OR DURING EJECTION
16. A/C ATTITUDE - AVOID SENSITIVITY TO A/C AND SEAT ATTITUDE IN THE WINDBLAST
17. RELIABILITY - ACHIEVE FUNCTIONAL RELIABILITY EQUIVALENT TO OTHER ESCAPE SUBSYSTEMS
18. MAINTAINABILITY - AVOID ADDING BURDENSOME MAINTENANCE TASKS TO THE ESCAPE SYSTEM
19. OPERATIONAL ACCEPTABILITY - AVOID CREW OR COMMAND RESISTANCE BY EMPHASIZING SIMPLICITY, LIGHT WEIGHT, RUGGEDNESS, AND LOW PERCEPTIBILITY BY FLIGHT CREWS
20. LOGISTICS - MINIMIZES LOGISTICS BURDEN BY FAVORING ON-SEAT, UNIVERSAL FIT DESIGN

SYMBOL LEGEND

" RELATIONS BETWEEN REQUIREMENTS

B - BENEFICIAL
N - NEUTRAL
C - CONTRADICTORY

NOTE: THE NUMBERS BELOW THE C'S REFER TO THE ENTRIES IN TABLE III, "INTERACTION MATRIX CONTRADICTIONS: EXPLANATIONS AND RESOLUTIONS"

Table 2.

INTERACTION MATRIX CONTRADICTIONS: EXPLANATIONS AND RESOLUTIONS

	CONTRADICTIONS	EXPLANATION	SUGGESTED APPROACHES TO RESOLUTION
1	Crew size vs. design to cost.	Accommodating full range of crew sizes tends to drive up cost for adjustments, testing and logistics.	Trade study of cost-benefit of personal fit individually assigned items vs. universal, adjustable "one size" items. Attempt to locate supports in areas with minimal size variation of human body dimensions.
2	Crew size vs. weight.	Accommodating full range of crew sizes tends to drive up weight. Larger men require more material. Longer range of adjustment requires more material. Heavier men require stronger parts to restrain loads, higher drag forces.	Attempt to locate supports in areas with minimal size variation of human body dimensions. Consider individual fit to reduce size of hardware, extra material for adjustments.
3	Crew size vs. seat stability.	Positioning of crew to prevent flail could change center of mass drag location and thus seat stability. (Aggravated by wide range of crew sizes.)	Attempt to restrain limbs in positions which maintain design center of mass during ejection. Analysis is required to show the magnitude of the impact.
4	Crew size vs. manual release accessibility.	Anthropometric variations may cause difficulty in reaching emergency release handle during restraint.	Mock-up evaluation of concept. Provide adequate slack in restraint system, potentially self defeating. Change location of manual release control.

Table 2. (Continued)

INTERACTION MATRIX CONTRADICTIONS: EXPLANATIONS AND RESOLUTIONS

CONTRADICTIONS	EXPLANATION	SUGGESTED APPROACHES TO RESOLUTION
5 Crew size vs. ingress/donning.	Accommodating a wide range of crew size could imply adjustment to be performed during ingress/donning.	Mock-up evaluation of concepts. Attempt to design for restraint at areas of minimal variability. Provide individual fit garments (integrated harness) for crew which incorporate major problems of adjustment, minimizing those needed for ingress.
6 Crew size vs. drag and inertial forces. 7 Crew size vs. pre-ejection positioning.	Job of designing pre-ejection positioning devices and restraints against drag and inertial forces is made more difficult by wide range of body sizes.	Analyze maximum and minimum sizes of crew to determine sensitivity of design to these effects.
8 Crew size vs. load distribution.	Crew size range affects fit within primary harness. Loose fit may reduce primary restraint loads-permit high loads on limb restraints.	Mock-up fit tests can give strong indication of whether this can be a serious problem. Tilt table tot with load cells can also help. Design out of system.
9 Personal equipment vs. design to cost.	Preserving reach and vision and access to personal equipment may require extensive development to assure satisfactory solution.	Early planning and careful attention to definition and location of personal equipment helps reduce design and development false starts.

Table 2. (Continued)

INTERACTION MATRIX CONTRADICTIONS: EXPLANATIONS AND RESOLUTIONS

	CONTRADICTIONS	EXPLANATION	SUGGESTED APPROACHES TO RESOLUTION
10	Personal equipment vs. seat separation.	Personal equipment may involve separate seat man interfaces (communications, oxygen) which are potential problems at separation due to entanglement.	Monitor potential entanglement situations. Assure position, fail safe separation of limb/head restraints if they become items of personal equipment.
11	Personal equipment vs. drag & inertial forces.	Personal equipment tends to interfere with pre-ejection positioning and deployment of limb/head restraint systems which drag and inertial forces.	Overcome interference of personal equipment. Route restraints to clear personal equipment or contain it.
12	Personal equipment pre-ejection positioning.	Drag and inertial forces may tend to separate personal equipment from ejectee. Variation between winter/summer flight clothes increases operation range of system.	Determine need for restraint system to contain or restrain personal equipment as well as limbs and head.
13	Personal equipment vs. logistics.	Limb restraints and head restraints which become personal equipment items add to logistics burden (accounting, purchasing, storage, issue, spares stocking)	Attempt to minimize new items to be procured. Integrate with other items to reduce stocking problems. Consider adjustability vs. variations in sizes.

Table 2. (Continued)

INTERACTION MATRIX CONTRADICTIONS: EXPLANATIONS AND RESOLUTIONS

CONTRADICTIONS	EXPLANATION	SUGGESTED APPROACHES TO RESOLUTION
14 Crew Size vs. logistics	Possible conflict due to decision to provide limb restraint devices in two or more sizes to accommodate wide range of crew body dimensions.	Attempt to use one size with adjustability to fit all crew variability in body dimensions.
15 Seat separation vs. logistics.	A potential need for a new seat separation device impacts logistics.	Attempt to use existing seat separation devices.
16 Drag and inertial forces vs. logistics.	An implied need for new devices to resist drag and inertial forces on head and limbs impacts logistics considerations.	Minimize number of devices needed to resist drag and inertial forces on head and limbs.
17 Pre-ejection positioning vs. logistics.	An implied need for new devices to pre-position the crew limbs and head impacts logistics considerations.	Minimize number of devices needed to pre-position head and limbs.
18 Reach vs. design to cost.	Providing adequate reach may increase development cost in complicating the restraint system.	Keep designs as simple as possible consistent with adequate reach capability.
19 Vision vs. design to cost.	Providing adequate vision in cockpit may increase development cost in complicating the restraint system.	Keep designs as simple as possible consistent with adequate vision capability.

Table 2. (Continued)

INTERACTION MATRIX CONTRADICTIONS: EXPLANATIONS AND RESOLUTIONS

CONTRADICTIONS	EXPLANATION	SUGGESTED APPROACHES TO RESOLUTION
20 Reach vs. ingress/donning. 21 Reach vs. egress/doffing.	Loop-over straps may avoid extra tasks but impede reach.	Design adequate slack in system to avoid impeding reach.
22 Reach vs. drag and inertial forces. 23 Vision vs. drag and inertial forces.	Devices to resist drag and inertial forces could restrict reach and vision.	Design to minimum impact on crew reach, vision and general mobility in cockpit.
24 Reach vs. pre-ejection positioning. 25 Vision vs. pre-ejection positioning.	Pre-ejection positioning equipment may compromise reach and vision.	Design to minimize impact of pre-ejection positioning equipment on reach and vision. Keep slim, low profile and avoid shoulder projections.
26 Reach vs. a/c attitude. 27 Vision vs. a/c attitude.	Guards to protect crew against side wind forces may interfere with reach and vision.	Keep guards minimal during operational phase.
28 Vision vs. ingress/donning and vs. 29 Egress/doffing.	Loop-over straps may avoid extra tasks, but interfere with vision.	Minimize visual interference by careful location of restraint straps.

Table 2. (Continued)

INTERACTION MATRIX CONTRADICTIONS: EXPLANATIONS AND RESOLUTIONS

CONTRADICTIONS	EXPLANATION	SUGGESTED APPROACHES TO RESOLUTION
30 Cost vs. weight.	Trimming weight of ten induces higher RDT&E costs (but reduces ejected weight)	No clear-cut solution is available. Weight minimization, however, is necessary in aircraft equipment design.
31 Cost vs. seat stability.	Assurance of aerodynamic stability by added devices or seat modifications could be costly.	Design to avoid instability aggravation, but not to include seat stabilization in order to reduce limb flail.
32 Cost vs. seat separation.	Added devices could increase cost.	Attempt to minimize need for extra seat separation devices.
33 Cost vs. manual release accessibility.	Preserving/assuring manual relsase capability could induce higher development costs than if requirement ignored.	Select system which does not compromise reach and hopefully which is inherently capable with complex modifications.
34 Cost vs. ingress/donning and 35 Vs. egress/doffing.	Development costs are often higher to achieve simplicity and convenience of <u>operation</u> (as opposed to mechanical simplicity).	Ease of ingress and egress is a prime crew acceptance item and must not be seriously compromised. An investment in this area is probably worth the cost.
36 Cost vs. drag and inertial forces protection.	Added devices tend to increase cost to procure system.	Keep design simple and easy to manufacture. The protection against drag and inertial forces is prime objective of study - must be met.

Table 2. (Continued)

INTERACTION MATRIX CONTRADICTIONS: EXPLANATIONS AND RESOLUTIONS

CONTRADICTIONS	EXPLANATION	SUGGESTED APPROACHES TO RESOLUTION
37 Cost vs. pre-ejection positioning. 38 Cost vs. a/c attitude.	Added devices tend to increase cost to procure.	Desired protection is among key objectives of study investment is required to achieve objective.
39 Cost vs. reliability.	Cost reduction at initial development may reduce reliability (but improved reliability may reduce life cycle costs).	Trade study to analyze cost impacts. Keep design simple to aid reliability.
40 Weight vs. seat stability and 41 Weight vs. a/c attitude	Large mass on seat tends to make seat stable and less sensitive to a/c attitude but adverse CG shift can destabilize also ejected weight goals are compromised (119).	Effect probably negligible for this study. Keep weight minimal and forward.
42 Weight vs. seat separation.	Fail-safe, positive separation system may require redundancy and thus extra weight.	Analysis of failure modes, reliability and backup devices to minimize weight with adequate safety. Test to verify.
43 Weight vs. drag and inertial forces.	Added devices to resist drag and inertial forces can increase weight.	Design for minimum weight by materials selection and analysis of stresses.
44 Weight vs. egress/ doffing.	Additional strip lengths may be needed to minimize tasks in egress (probably small impact).	Design for minimum weight consistent with function.

Table 2. (Continued)

INTERACTION MATRIX CONTRADICTIONS: EXPLANATIONS AND RESOLUTIONS

CONTRADICTIONS	EXPLANATION	SUGGESTED APPROACHES TO RESOLUTION
45 Weight vs. pre-ejection positioning.	Pre-ejection positioning device may add weight to limb restraint system particularly power devices.	See preceding statement. Attempt to combine functions to save weight.
46 Weight vs. reliability.	Weight reduction is frequently in conflict with reliability especially where redundancy is applied.	Design for minimum weight consistent with estimated reliability.
47 Seat stability vs. drag & inertial forces.	ACES II seat now divergent under drag and inertial forces. Potentially limb restraint system could either aid or worsen seat stability.	This is an unclear relationship. No action to resolve known at this time. Designs should attempt to enhance stability at a minimum not degrade it.
48 Seat separation vs. reliability.	Reliable seat separation is critical and difficult to achieve and prove.	Designs should not degrade seat separation, but enhance it.
49 Seat separation vs. maintainability.	Additional separation mechanisms are potential source of maintenance inspection, servicing, replacement. May add to seat removal and replacement functions.	Keep design accessible, simple, reliable.
50 Manual release accessibility vs. drag & inertial forces.	Easy access conflicts with devices to restrict arm motion due to aerodynamic and g-forces.	Design to accomplish both functional requirements. Keep lower arm relatively free. Move manual release control.

Table 2. (Continued)

INTERACTION MATRIX CONTRADICTIONS: EXPLANATIONS AND RESOLUTIONS

	CONTRADICTIONS	EXPLANATION	SUGGESTED APPROACHES TO RESOLUTION
51	Manual release accessibility vs. pre-ejection positioning.	Pre-ejection positioning implies restriction on arm mobility.	See preceding statement.
52	Manual release accessibility vs. a/c attitude.	Objective of protection regardless of a/c attitude tends to constrain design for manual release accessibility.	See above.
53	Landing entanglement avoidance vs. drag and inertial forces.	Nets and longstraps attached to occupant for resisting drag and inertial forces tend to increase entanglement risk.	Avoid nets. Minimize number and length of item attached to the occupant.
54	Landing entanglement avoidance vs. a/c attitude.	Nets and straps are obvious devices to resist effects of varying aircraft attitude but create entanglement problems.	Avoid nets and long straps.
55	Drag and inertial forces vs.	Improved restraints tend to complicate ingress/donning and egress/doffing by requiring added hookups/detachments.	Minimize hookup points.
56	Ingress/donning and vs. egress/doffing.		

Table 2. (Continued)

INTERACTION MATRIX CONTRADICTIONS: EXPLANATIONS AND RESOLUTIONS

CONTRADICTIONS	EXPLANATION	SUGGESTED APPROACHES TO RESOLUTION
57 Pre-ejection positioning vs. 58 Ingress/donning and vs. egress/doffing.	Potential difficulties in meeting both goals.	Minimize hookup points and impact of pre-ejection positioning apparatus.
59 A/C attitude vs. ingress donning and 60 Vs. egress/doffing.	Adequate coverage by restraints for insensitivity to a/c attitude may complicate normal ingress and both normal and emergency egress.	No clear method to resolve at this time. Favor solutions to A/C attitude problem which minimize impact on ingress/donning egress/doffing.
61 Reliability vs. ingress donning and 62 Vs. egress/doffing.	Added functions tend to decrease reliability of harness hookup.	Design for maxim possible reliability within constraint of functional requirement. Minimize hookup tasks.
63 Drag and inertial forces vs. a/c attitude.	Difficult to achieve protection in some attitudes.	Use omni-direction restraint system.
64 Drag and inertial forces vs. operational acceptability.	Devices to resist drag and inertial forces could be burdensome to crew.	Minimize effect on crew operations. Educational effort as to necessity.

Table 2. (Continued)

INTERACTION MATRIX CONTRADICTIONS: EXPLANATIONS AND RESOLUTIONS

CONTRADICTIONS	EXPLANATION	SUGGESTED APPROACHES TO RESOLUTION
65 Load distributions vs. a/c attitude.	Varying a/c attitudes creates wide range of unusual load distributions and makes it difficult to avoid loading limb restraint with main body loads.	Use omni-directional restraint systems.
66 Pre-ejection positioning vs. reliability.	Limb positioning mechanism may add complexity and thus reduce reliability.	Keep design as simple as possible and design for inherent reliability.
67 Pre-ejection positioning vs. maintainability.	Mechanism to preposition may add to maintenance requirements.	Design for minimum maintenance.
68 Pre-ejection positioning vs. operational acceptability.	Potential conflict between devices which positively pre-position limbs and need for freedom of mobility in cockpit and avoidance of nuisance of added hookups.	Minimize conflicts by careful design. Interview pilots to determine special problems of crew acceptability.
69 Logistics vs. ingress. 70 Logistics vs. egress.	Simplification of ingress donning and egress/doffing may conflict with or impact logistics considerations by adding more personal equipment (as integrated harness) instead of single, adjustable, aircraft-mounted device.	Trade study of impacts.

Table 2. (Continued)

INTERACTION MATRIX CONTRADICTIONS: EXPLANATIONS AND RESOLUTIONS

CONTRADICTIONS	EXPLANATION	SUGGESTED APPROACHES TO RESOLUTION
71 Load distribution vs. pre-ejection positioning.	Loads required to pre-position may take up main body restraint loads in place of primary restraint system (153).	Careful selection of load paths and anchor points for entire system.
72 Personal equipment vs. weight.	Clearance between restraint system and personal equipment may increase weight.	Seek minimum weight support systems in light of personal equipment locations and constraints. Problem is highly specific - not subject to generalized resolution approach. May be non-existent in specific cases. Map locations of personal equipment on body, with dimensions for range of crew sizes.
73 Maintainability vs. logistics.	Reducing number of parts to be stocked and tracked may increase problems of accessibility by limiting system design to items attached to seat (vs. personal equipment items).	Perform trade study of impact to logistics and maintainability.
74 Logistics vs. operational acceptability.	Design for minimum impact on logistics could result in requirements for crew to make multiple adjustments on restraint system before flight - inconvenience reduces crew acceptability and scramble readiness.	Perform trade study to assess impacts on crew acceptability and logistics. Favor crew acceptability where possible.

Table 2. (Concluded)

INTERACTION MATRIX CONTRADICTIONS: EXPLANATIONS AND RESOLUTIONS

CONTRADICTIONS	EXPLANATION	SUGGESTED APPROACHES TO RESOLUTION
75 Crew size vs. maintainability.	Wide size range in separately sized limb restraints could impact logistics.	Attempt to use small number of sizes (one) or/and adjust to individual (as personal equipment item).
76 Landing entanglement avoidance vs. pre-ejection positioning.	Devices to pre-position could induce entanglement at landing if retained on occupant.	Design to preclude entanglement. Assure positive separation. Use short lengths of strap Try to divest entire system at seat-man separation.

Fourth, satisfaction of the operational needs of the using command, e.g. logistics, maintainability, etc.

These criteria were used to rank order the design requirements as shown in Table 3. The list of rank ordered requirements was then used to form a second interaction matrix, shown in Table 4. In this new matrix the previously identified interactions are automatically organized by importance and tradeability. The vertical axis represents importance in the sense of rank order and the horizontal axis represents tradeability in the sense of its representing the difference in rank order between the conflicting requirements. If the rank order difference is small, the size of the trade-off should be small but the direction of trade-off is justifiable either way. If the rank order difference is large, a large trade-off may be justifiable but it is difficult to justify the trade-off of a higher ranked requirement for a lower ranked one.

A second aim of the design requirements analysis was to prepare a description of the open-seat ejection event which would tie together, by association, the available information about the principle elements, namely the air, the man, and the seat. Toward this end a chart was prepared which showed the relationship between the event timeline of the seat and the time histories of dynamic pressure and deceleration for a typical high-speed low-altitude ejection. This chart is presented in Figure 1.

Also discussions were prepared on the importance of frame of reference to ejection force descriptions, and on the sequence of events which lead to the creation of the ejection forces.

A third aim of the requirements analysis effort was to identify the injury vulnerabilities of the seat occupant and to describe the implications for limb restraint designs.

An effort to develop design and evaluation criteria was carried out concurrently with the design requirements analysis. The approach was to compile a table of design and evaluation criteria based on the list of requirements and the requirement conflict descriptions, taken from Tables 1 and 2. This table of criteria is shown in Table 5.

The next effort was aimed at design conceptualization. At the start, this effort was open to all previous design solutions and any new method or technique for protecting against windblast injuries. Later the effort was scoped down to development of configurations and deployment techniques for the broad category of strap type limb-restraint systems. This change of scope was based on the determination that strap type systems offered the best overall performance and also that the design flexibility inherent

TABLE 3. SEPARATION OF DESIGN REQUIREMENTS BY MISSION AND BY IMPORTANCE TO A MISSION FOR THE PURPOSE OF BANK ORDERING THE DESIGN REQUIREMENTS

	Missions			
Rank	Aircraft	Escape System	Crew	Using Command
1	Weight			
2		Drag & Inertial Forces		
3		A/C Attitude		
4			Vision	
5			Reach	
6				DTC/LCC
7		Pre-ejection Positioning		
8		Seat Separation		
9		Load Distribution		
10		Crew Size	Crew Size	
11				Logistics
12		Personal Equipment	Personal Equipment	
13		Landing Entanglement		
14		Emergency Egress	Emergency Egress	
15			Manual Release Accessibility	
16		Seat Stability		
17			Ingress/ Donning	
18				Operational Acceptability
19				Reliability
20				Maintainability

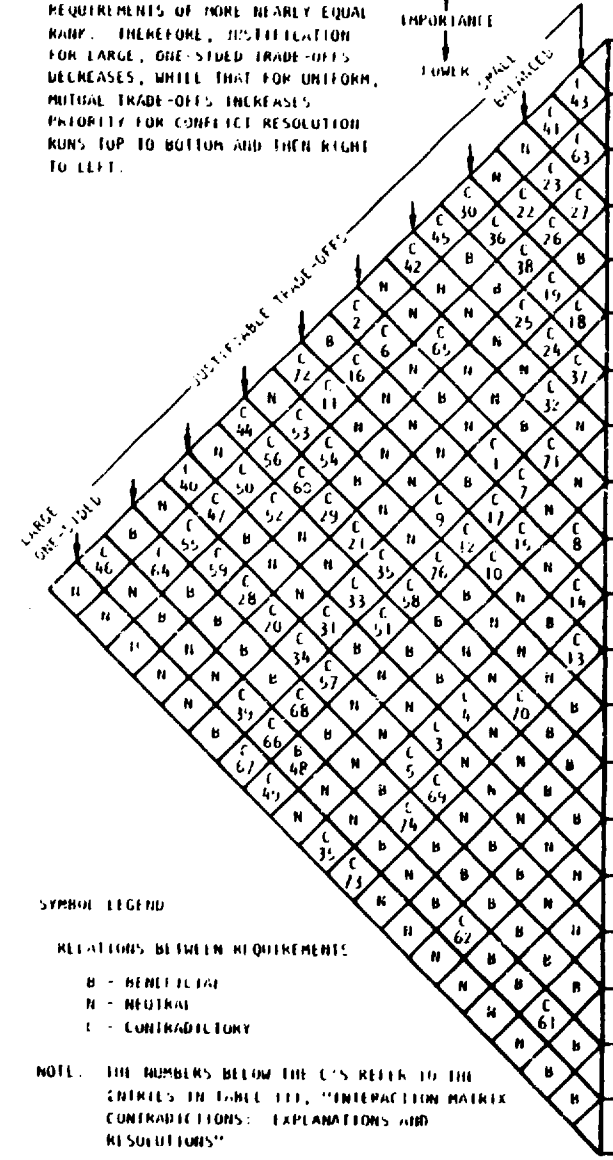
Table 4. INTERACTION MATRIX WITH RANK ORDERED REQUIREMENTS

NOTE. FROM LEFT TO RIGHT ACROSS THE MATRIX, INTERACTIONS ARE BETWEEN REQUIREMENTS OF MORE NEARLY EQUAL RANK. THEREFORE, JUSTIFICATION FOR LARGE, ONE-SIDED TRADE-OFFS DECREASES, WHILE THAT FOR UNIFORM, MUTUAL TRADE-OFFS INCREASES. PRIORITY FOR CONFLICT RESOLUTION RUNS TOP TO BOTTOM AND THEN RIGHT TO LEFT.

HIGHER

IMPORTANCE

LOWER



RANK ORDERED DESIGN REQUIREMENTS

1.	WEIGHT - KEEP WEIGHT TO MINIMUM LEVEL CONSISTENT WITH ACHIEVEMENT OF MISSION OBJECTIVES
2.	DRAG AND INERTIAL FORCES - APPLY FORCES TO, OR SHIELD, THE HEAD AND LIMBS TO PREVENT HAZARDOUS RELATIVE MOVEMENT BETWEEN THESE AND THE TORSO
3.	A/C ATTITUDE - AVOID SENSITIVITY TO A/C AND SEAT ATTITUDE IN THE WINDBLAST
4.	VISION - PRESERVE THE INTERNAL AND EXTERNAL VISIBILITY ENJOYED BY THE SEAT OCCUPANT
5.	REACH - PRESERVE THE REACH ACCESSIBILITY OF CONTROLS AND EQUIPMENT INTENDED FOR USE BY THE SEAT OCCUPANT
6.	DESIGN TO COST/LIFE CYCLE COST - KEEP DEVELOPMENT AND LIFE CYCLE COSTS TO MINIMUM LEVEL CONSISTENT WITH ACHIEVEMENT OF MISSION OBJECTIVES
7.	PRE-EJECTION POSITIONING - AVOID SENSITIVITY TO THE PRE-EJECTION POSITION OF THE BODY AND LIMBS BY AUTOMATICALLY POSITIONING THEM BEFORE OR DURING EJECTION
8.	SEAT SEPARATION - PROVIDE POSITIVE FAIL-SAFE RELEASE OF ANY ACTIVE RESTRAINTS AT THE SAME TIME AS PRIMARY RESTRAINT RELEASE
9.	LOAD DISTRIBUTION - LET THE PRIMARY RESTRAINT SYSTEM CARRY THE MAJOR LOADS DUE TO DECELERATION BETWEEN THE SEAT AND TORSO
10.	CREW SIZE - ACCOMMODATE AND BE FUNCTIONALLY INSENSITIVE TO ALL VARIABILITY IN CREW SIZE
11.	LOGISTICS - MINIMIZES LOGISTICS BURDEN BY FAVORING ON-SEAT, UNIVERSAL FIT DESIGN
12.	PERSONAL EQUIPMENT - ACCOMMODATE AND BE FUNCTIONALLY INSENSITIVE TO ANY PERSONAL EQUIPMENT LIKELY TO BE WORN BY THE EJECTION SEAT OCCUPANT
13.	LANDING ENTANGLEMENT AVOIDANCE - AVOID NETS OR STRAPS WHICH MIGHT ENTANGLE AN EJECTEE'S LIMBS DURING LANDING
14.	EGRESS (EMERGENCY)/DOFFING - INTEGRATE ANY RESTRAINTS WITH THE PRIMARY RESTRAINT SINGLE POINT RELEASE AND AVOID EXTRA DOFFING TASKS
15.	MANUAL RELEASE ACCESSIBILITY - PRESERVE THE SEAT OCCUPANT'S ACCESS TO THE MANUAL RESTRAINT RELEASE HANDLE
16.	SEAT STABILITY - PRESERVE OR IMPROVE THE AERODYNAMIC STABILITY OF THE SEAT
17.	INGRESS/DONNING - AVOID COMPLICATION OF THE INGRESS PROCEDURE AND ADDITION OF EXTRA ATTACHMENT TASKS
18.	OPERATIONAL ACCEPTABILITY - AVOID CREW OR COMMAND RESISTANCE BY EMPHASIZING SIMPLICITY, LIGHT WEIGHT, RUGGEDNESS, AND LOW PERCEPTIBILITY BY FLIGHT CREWS
19.	RELIABILITY - ACHIEVE FUNCTIONAL RELIABILITY EQUIVALENT TO OTHER ESCAPE SUBSYSTEMS
20.	MAINTAINABILITY - AVOID ADDING BURDENSOME MAINTENANCE TASKS TO THE ESCAPE SYSTEM

SYMBOL LEGEND

RELATIONS BETWEEN REQUIREMENTS

- B - BENEFICIAL
- N - NEUTRAL
- C - CONTRADICTORY

NOTE. THE NUMBERS BELOW THE C'S REFER TO THE ENTRIES IN TABLE III, "INTERACTION MATRIX CONTRADICTIONS: EXPLANATIONS AND RESOLUTIONS"

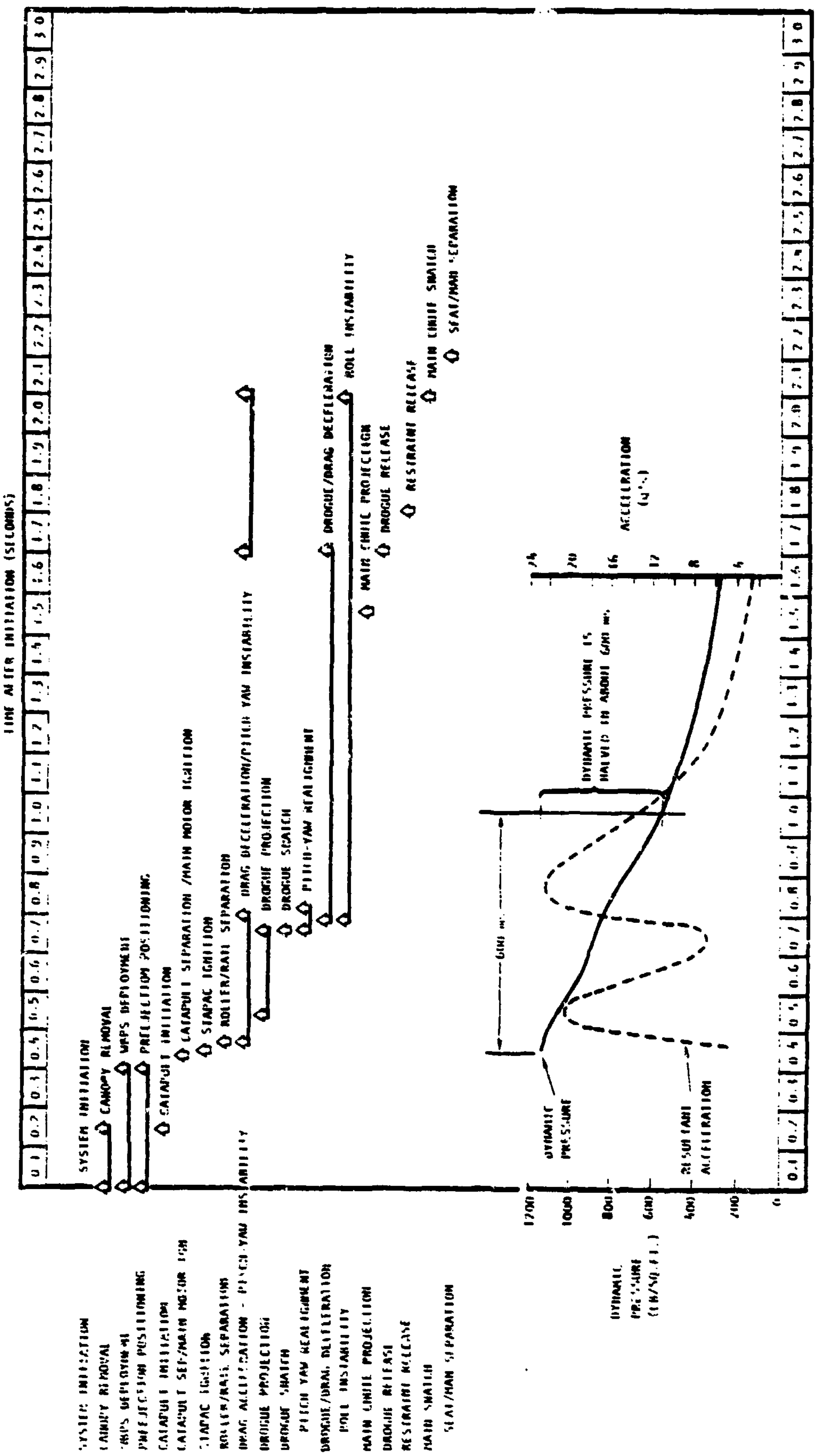


Figure 1. Event/Dynamic Timeline for Typical High-Speed Ejection

Table 5.

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS: DESCRIPTION	QUANTIFIABLE ASPECTS: DATA SOURCE	QUANTIFIABLE ASPECTS: EVAL. METHOD
1. <u>CREW SIZE</u>	Accommodate all variability in crew size	. Basic percentiles, statistics	Tables: MIL-STD 1472B	Drawings inspection (where applicable dimensions are used)
CONFLICTING FACTORS: 1 Cost 2 Weight 3 Seat Stability 4 Manual Release Accessibility 5 Ingress/Donning Egress/Doffing 6 Drag & Inertial Forces 8 Load Distribution 7 Pre-Ejection Positioning 75 Maintainability 14 Logistics BENEFICIAL FACTORS: Reach Operational Acceptability Crew Size	*CRITERIA:* Ideal: smallest to largest person in crew Realistically high level: 1st to 99th percentile Minimal: 5th to 95th percentile *QUALIFICATIONS:* Specified population (Males, 1967, U.S.A.F. aircrew)	. Calculated ranges for design Midshoulder height, sitting Shoulder height, sitting Shoulder breadth Elbow rest height, sitting Elbow-elbow breadth Shoulder-elbow length Elbow-wrist length Chest breadth Hip breadth *Abdominal depth* Shoulder circumference Chest circumference Thigh clearance height Buttock-knee length *Knee height (sitting)* Weight	AFSC DH2-2 Unpubl. computer printout - aircrew body dimensions NASA: Anthropometric Source Book. RP 1024 (1978)	Subject selection measurements for mockups and prototype evaluation Dummies selection for ejection tests and/or wind tunnel tests
		. Workspace design dimensions . Subject to design concept *selection* . Subject to seat design in which protection system is to be installed . Subject to aircraft cockpit design	. Ejection envelope per MIL-S-9479 . Mock-up test results . ACES II Engineering drawings & prototypes . Drawings of aircraft cockpit, eject. envelopes	Mock-up/Prototype evaluation with dummies and human subjects as appro-[illegible]e

Table 5. (Continued)

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS DESCRIPTION	DATA SOURCE	EVAL. METHOD
2. **PERSONAL EQUIPMENT** **CONFLICTING FACTORS:** 9 Cost 72 Weight 10 Seat Separation 11 Drag & Inertial Forces 12 Pre-Ejection Positioning 13 Logistics **BENEFICIAL FACTORS:** Landing entanglement avoidance. Egress/Doffing. Operational Acceptability.	Accommodate any personal equipment likely to be worn by seat occupant - - - - - - - - - CRITERIA: 1. Restraint system does not impede access to personal equipment or obstruct function. 2. Restraint system does not hang up nor have reduced effectiveness as a result of personal equipment being worn.	Envelope of configuration Reach Access Locations on crew body or seat interface Weight Attachment strength Drag forces expected (which may tear off item)		Drawing inspection Prototype and mock-up evaluation tests using human subjects Wind tunnel tests Ejection tests using dummies.

Table 5. (Continued)

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS: DESCRIPTION	DATA SOURCE	EVAL. METHOD
3. REACH (Includes limb clearance) CONFLICTING FACTORS: 18 Cost 20 Ingress/Donning 21 Egress/Doffing 23 Drag & Inertial Forces 24 Pre-Ejection Positioning 26 A/C Attitude BENEFICIAL FACTORS: Vision Operational Acceptability Crew Size	Preserve access to controls/equipment intended for seat occupant CRITERIA: Ideal: All subjects can reach all controls and equipment. No clearance problems. (No exceptions allowed) QUALIFICATIONS: . Applicable to all crew sizes . Varies according to aircraft as regards reach envelopes	. Number of controls/equipment items reachable . Distance to controls/equipment beyond maximum reach.	Mock-up test results	Mock-up evaluation using human subjects

Table 5. (Continued)

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS: DESCRIPTION	QUANTIFIABLE ASPECTS: DATA SOURCE	QUANTIFIABLE ASPECTS: EVAL. METHOD
4. <u>VISION</u> <u>CONFLICTING FACTORS:</u> 19 Cost 28 Ingress/Donning 29 Egress/Doffing 23 Drag/Inertial Forces 25 Pre-Ejection Position 27 A/C Attitude <u>BENEFICIAL FACTORS:</u> Reach. Landing Entanglement Avoidance. Operational Acceptability.	Preserve internal and external visibility enjoyed by seat occupant - - - - - - - - - - - CRITERIA: Ideal: No decrement Realistic: No functional performance decrement (Visual obstruction is not critical).	No. of displays and equipment visible (or area obstructed)	Mock-up test results	Mock-up evaluation using human subjects.

Table 5. (Continued)

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS: DESCRIPTION	QUANTIFIABLE ASPECTS: DATA SOURCE	EVAL. METHOD
5. COST CONFLICTING FACTORS: 1 Crew Size 8 Personal Equip. 18 Reach 19 Vision 30 Weight 31 Seat Stability 32 Seat Separation 33 Manual Release 34 Ingress 35 Egress 36 Drag/Inertial Forces 37 Pre-Ejection Positioning 38 A/C Attitude 39 Reliability BENEFICIAL FACTORS: Logistics	Keep development and life cycle costs to minimum, consistent with achievement of mission objectives	. Estimated cost of the concept . Development . Procurement (Materials Manufacturing) . Maintenance . Logistics	USAF Cost Estimating Handbooks Sound Engineering Judgement	. Monitor Total Development Costs . Interview logistics specialists and maintenance specialists

Table 5. (Continued)

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS		
		DESCRIPTION	DATA SOURCE	EVAL. METHOD
6. WEIGHT CONFLICTING FACTORS: 2 Crew Size 72 Personal Equipment 30 DTC/LCC 40 Seat Stability 42 Seat Separation 44 Egress/Doffing 43 Drag and Inertial Forces 45 Pre-Ejection Positioning 41 A/C - Attitude 46 Reliability BENEFICIAL FACTORS: Operational Acceptability Logistics	Minimize weight, consistent with meeting mission objectives - - - - - - - - CRITERIA: (TBD) • System should be no heavier than DAC ACES B-1 System REALISTIC: • System weight will improve escape system acceleration performance	Weight of each item can be estimated	Materials density data and historical experience	Scale-weigh

Table 5. (Continued)

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS: DESCRIPTION	QUANTIFIABLE ASPECTS: DATA SOURCE	EVAL. METHOD
7. SEAT STABILITY CONFLICTING FACTORS: 3 Crew Size 31 DTC/LCC 40 Weight 47 Drag and Inertial Forces BENEFICIAL FACTORS: Pre-Ejection Positioning A/C Attitude Reliability Operational Acceptability	Preserve or improve the aerodynamic stability	. Change of seat/man C.G. due to system installation . Moments due to misalignment of C.G. and center-of-drag . Change of moments of inertia of seat/man . Change of limb positions due to system deployment . Change of center-of-drag at various altitudes	. DAC Report of Design C.G. Envelope . RI Report of test C.G. envelope . AMRL Reports on seat stability TR-75-15 TR-75-8 TR-73-24 TR-76-3 TR-74-9	. Seat CG measurements using human subjects . Analysis of previous wind tunnel testing and system confg. . Measurement of seat man moment-of-inertia with human subjects. . Optional wind tunnel testing of system with human subjects

Table 5. (Continued)

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS: DESCRIPTION	QUANTIFIABLE ASPECTS: DATA SOURCE	QUANTIFIABLE ASPECTS: EVAL. METHOD
8. <u>SEAT SEPARATION</u> <u>CONFLICTING FACTORS</u>: 10 Personal Equipment 32 Design to Cost/LCC 42 Weight 49 Maintainability 15 Logistics <u>BENEFICIAL FACTORS</u>: Manual Release Accessibility Landing Entanglement Avoidance Egress (Emergency)/Doffing Reliability Operational Acceptability	Provide positive fail-safe release of any active restraints at the same time as primary restraint release. Ideal: Use only the restraint releases found on the basic ACES II seat plus leg restraint releases.	. No quantifiable aspects . Demonstrable aspects . Dummy and human subject tests show smooth separation of seat and man after system release . The system does not interface with disconnection of O_2 or Com. lines . System is not sensitive to adverse attitude separations . System release mechanism . Design minimizes cost within performance goals . Few new release points . Maximum use of main restraint release points . Design minimizes weight within performance goals . Same as above . Uses light weight materials/components . Design is maintainable . Uses off-shelf components/materials . Is accessible in cockpit . Is resettable in cockpit	. Sound engineering judgement	. Tower drop tests to demonstrate separation smoothness (slow-mo-photog) . Controlled separation tests with human subjects . Prototype design review . For DTC/LCC . For weight . For maintainability . Mock-up demonstration of cockpit accessibility, resettability . For logistics

Table 5. (Continued)

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS: DESCRIPTION	QUANTIFIABLE ASPECTS: DATA SOURCE	QUANTIFIABLE ASPECTS: EVAL. METHOD
8. <u>SEAT SEPARATION</u> (Concluded)		. Design minimizes logistics burden . Is insensitive to crew size . Few new parts . Low unit price . Long life cycle		

Table 5. (Continued)

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS: DESCRIPTION	DATA SOURCE	EVAL. METHOD
9. **MANUAL RELEASE ACCESSIBILITY** **CONFLICTING FACTORS:** 4 Crew Size 33 Design to Cost/LCC 50 Drag & Inertial Forces 51 Pre-Ejection Positioning 52 A/C Attitude **BENEFICIAL FACTORS:** Seat Separation Landing Entanglement Avoidance Egress (Emergency)/Doffing Load Distribution Reliability Operational Acceptability	Deployed WBP system allows seat occupant to reach and actuate manual release control	. Specific maneuver required to gain freedom from restraints . Demonstrable aspects . Maneuver is within capability of all sizes of occupants . Design minimizes cost within performance goals . Maneuverability is incorporated in the basic design . Relocation of the restraint release trigger if not required . Capability implemented with low-cost materials, simple design . Design does not compromise windblast injury protection . Low probability of drag and/or inertial forces simulating voluntary release maneuver . Freedom of movement does not allow hazardous build up of differential velocity between arms and body or seat . Design does not compromise ejection positioning capabilities	. Sound engineering judgement	. Demonstrate manual release access and actuation using human subjects covering a range of sizes and the ACES II seat with current manual release location. . Design review . For DTC/LCC . For compatibility with drag and inertial force resistance . For compatibility with pre-ejection positioning . For insensitivity to a/c attitude

Table 5. (Continued)

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS DESCRIPTION	DATA SOURCE	EVAL. METHOD
9. <u>MANUAL RELEASE ACCESSIBILITY</u> (Concluded)		. Out of position arm is positioned but not immobilized for all crew sizes . Design is insensitive to a/c attitude at ejection		

Table 5. (Continued)

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS		
		DESCRIPTION	DATA SOURCE	EVAL. METHOD
10. LANDING ENTANGLEMENT AVOIDANCE CONFLICTING FACTORS: 53 Drag & Inertial Forces 76 Pre-Ejection Positioning 54 A/C Attitude BENEFICIAL FACTORS: Personnel Equipment Vision Seat Separation Manual Release Accessibility Ingress/Donning Egress (Emergency)/Doffing Reliability Operational Acceptability	No components on ejectee which might entangle his legs or arms in water	. No quantifiable aspects . Demonstrable aspects . No nets, straps or loops on ejectee when landing occurs . All components stay with the seat or are thrown free during seat/man separation	. Sound engineering judgment	. Demonstration of controlled release of restraints showing how ejectee is left free of potentially entangling components

Table 5. (Continued)

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS: DESCRIPTION	QUANTIFIABLE ASPECTS: DATA SOURCE	QUANTIFIABLE ASPECTS: EVAL. METHOD
11. INGRESS/DONNING CONFLICTING FACTORS: 5 Crew Size 20 Reach 28 Vision 34 DTC/LCC 55 Drag & Inertial Forces 57 Pre-Ejection Positioning 59 A/C Attitude BENEFICIAL FACTORS: Landing Entanglement Avoidance Egress (Emergency)/Doffing Reliability Operational Acceptability	Simple ingress procedure Avoid additional attachment tasks	. Detailed procedure for donning of the WBP system . Demonstrable aspects . Ingress to seat and attachment of restraints is minimally complicated by the WBP system . Donning of WBP system is insensitive to crew size . The design approach for this factor does not unjustifiably compromise reach, vision, DTC/LCC, protection from drag and inertial forces, pre-ejection positioning, or insensitivity to a/c attitude . This factor is important for operational acceptability. Tradeoffs against other factors, notably cost and pre-ejection positioning, are justifiable, if improvements in ingress/donning can be cited.	. Sound engineering	. Demonstrate ingress/donning in a simulated seat-cockpit work space using human subjects representing the full range of crew sizes . Design review . For DTC/LCC . For drag & inertial forces . For pre-ejection positioning . For a/c attitude sensitivity

Table 5. (Continued)

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS: DESCRIPTION	QUANTIFIABLE ASPECTS: DATA SOURCE	QUANTIFIABLE ASPECTS: EVAL. METHOD
12. EGRESS (EMERGENCY)/ DOFFING CONFLICTING FACTORS: 21 Reach 29 Vision 35 DTC/LCC 44 Weight 56 Drag & Inertial Forces 58 Pre-Ejection Positioning 60 A/C Attitude 62 Reliability 70 Logistics BENEFICIAL FACTORS: Personal Equipment Seat Separation Manual Release Accessibility Landing Entanglement Avoidance Ingress/Donning Operational Acceptability	After actuation of single point release occupant can egress quickly and safely. Doffing of system is simple with minimal maneuvering to shed restraints.	. No quantifiable aspects . Demonstrable aspects . Doffing of seat restraints and normal egress is minimally complicated by the WBP system . Doffing the WBP system under normal or emergency conditions is insensitive to crew size . The design approach for this factor does not unjustifiably compromise: reach, vision, DTC/LCC, weight, protection from drag and inertial forces, pre-ejection positioning, insensitivity to a/c attitude, or efficient logistics . This factor is relatively important. Tradeoffs against other factors notably cost and pre-ejection positioning are justifiably improvements in doffing egress can be cited.	. Sound engineering judgement	. Demonstration of emergency egress with human subjects covering the range of crew sizes. . Demonstration of normal doffing and egress wing human subjects

Table 5. (Continued)

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS: DESCRIPTION	DATA SOURCE	EVAL. METHOD
12. <u>EGRESS (EMERGENCY)/ DOFFING</u> (Concluded)		Actuation of the restraint release handle releases the NBP system so the occupant may rapidly egress without special maneuvering to free himself from the restraints.		

Table 5. (Continued)

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS: DESCRIPTION	QUANTIFIABLE ASPECTS: DATA SOURCE	QUANTIFIABLE ASPECTS: EVAL. METHOD
13. DRAG & INERTIAL FORCES CONFLICTING FACTORS: 6 Crew Size 11 Personal Equipment 22 Reach 23 Vision 36 BTC/LCC 43 Weight 47 Seat Stability 50 Manual Release Accessibility 53 Landing Entanglement Avoidance 55 Ingress/Donning 56 Egress (Emergency) Doffing 63 A/C Attitude 64 Operational Acceptability 16 Logistics BENEFICIAL FACTORS: Pre-Ejection Positioning	Through restraint or shielding prevent the buildup in the head and limbs relative to the torso of hazardous angular velocities induced by aerodynamic loading and by inertial responses to deceleration, spinning or drogue opening shock.	. Maximum load vectors for the limbs and head. . Demonstrable aspects . Restraint forces are distributed over large surface areas	AMRL TR-75-8 TR-75-15 TR-76-3	. Static load tests . Dynamic load texts . Impact sled . Wind tunnel . Captive sled

Table 5. (Continued)

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS: DESCRIPTION	QUANTIFIABLE ASPECTS: DATA SOURCE	QUANTIFIABLE ASPECTS: EVAL. METHOD
14. <u>LOAD DISTRIBUTION</u> <u>CONFLICTING FACTORS</u>: 8 Crew Size 71 Pre-Ejection Positioning 66 A/C Attitude <u>BENEFICIAL FACTORS</u>: BTC/LCC Manual Release Accessibility	Let the primary restraint system carry the major loads due to differential deceleration between the seat and torso. Lateral shift of the torso in the seat should not be arrested by the wind-blast protection system. Criteria: Design approach to load distribution: 1. Does not unjustifiably compromise pre-ejection positioning. 2. Is effective regardless of a/c attitude at ejection	. No Quantifiable aspects. . Demonstrable aspects . Little loading of WBP system occurs when the torso shifts laterally in the seat. . Limb restraint remains effective when the torso moves laterally.	. Sound engineering judgement	. Demonstrate restraint load distribution with human subjects representing the range of crew sizes. . WBP system to be deployed and tightened.

Table 5. (Continued)

CRITICAL DES[illegible] & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS: DESCRIPTION	DATA SOURCE	EVAL. METHOD
15. PRE-[illegible] POSIT[illegible] CONFLICTING FACTORS: 7 Crew Size 12 Personal Equipment 24 Reach 25 Vision 37 DTC/LCC 45 Weight 51 Manual Release Accessibility 76 Landing Entanglement Avoidance 57 Ingress/Donning 58 Egress (Emergency)/Doffing 71 Load Distribution 66 Reliability 67 Maintainability 68 Operational Acceptability 17 Logistics BENEFICIAL FACTORS: Seat Stability Drag & Inertial Forces A/C Attitude	T[illegible] [illegible]vide windblast protection to seat occupants who are out of position at initiation, the WBP system will apply positioning forces to out of position limbs.	. This factor implies the requirement for a separate power source for taking up WBPS slack. The source must be capable of retracting all of the slack in the WBS prior to canopy release. The final positioning of the arms and legs will occur during ejection and will be effected by the power from the rocket catapult.	. Sound engineering judgement . Inertia reel or actuator manufacturer	. Demonstrate WBP system limb pre-ejection positioning capability on an ejection seat catapult trainer with human subjects.

Table 5. (Continued)

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS: DESCRIPTION	DATA SOURCE	EVAL. METHOD
16. <u>A/C ATTITUDE</u> <u>CONFLICTING FACTORS</u>: 26 Reach 27 Vision 38 DTC/LCC 41 Weight 52 Manual Release Accessibility 54 Landing Entanglement Avoidance 59 Ingress/Donning 60 Egress (Emergency)/Doffing 63 Drag & Inertial Forces 65 Load Distribution <u>BENEFICIAL FACTORS</u>: Seat Stability Pre-Ejection Positioning	Avoid sensitivity to a/c attitude during ejection or seat attitude during deceleration.	. Insensitivity to a/c attitude during ejection implies deployment of the WBP system in adverse attitudes for windblast. Limb restraints or shields should prevent limb flail regardless of the direction of force on the limbs. . Demonstrable aspects . The design approach to achieve WBPS insensitivity to a/c or seat attitude does not unjustifiably compromise: . Reach . Vision . Design to cost/life cycle cost . Manual release accessibility . Landing entanglement avoidance . Ingress or donning . Emergency egress or doffing . Load distribution	. Sound engineering judgement	. Demonstrate insensitivty to a/c attitude or seat attitude with wind tunnel tests using human subjects. . Design review . Mock-up review

Table 5. (Continued)

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS: DESCRIPTION	DATA SOURCE	EVAL. METHOD
17. <u>RELIABILITY</u> <u>CONFLICTING FACTORS</u>: 39 Design to Cost/ LCC 46 Weight 61 Ingress/Donning 62 Egress (Emergency)/Doffing 66 Pre-Ejection Positioning <u>BENEFICIAL FACTORS</u>: Seat Stability Seat Separation Manual Release Accessibility Landing Entanglement Avoidance A/C Attitude Maintainability Operational Acceptability Logistics	The WPB system will successfully deploy and protect against windblast injuries to the limbs and head in 99% of all expected ejections up to 600 KEAS.	. The method for deploying and tightening the windblast protection system must be compatible with nearly all possible ejection configurations. . From the normal configuration . To any position of the arms in front of the shoulder and below the head. . The strength of the WBP system components should be sufficient to carry nearly all of the anticipatable loads for the ejection envelope.	. Sound engineering judgement . Functional tests	. Design review . Mock-up review . Development tests . Functional tests

Table 5. (Continued)

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS: DESCRIPTION	QUANTIFIABLE ASPECTS: DATA SOURCE	QUANTIFIABLE ASPECTS: EVAL. METHOD
18. MAINTAINABILITY CONFLICTING FACTORS: 75 Crew Size 49 Seat Separation 67 Pre-Ejection Positioning 73 Logistics BENEFICIAL FACTORS: DTC/LCC Reliability Operational Acceptability	Any servicible components of the MBP system will be placed so as to be readily serviceable. If any part of the MBPS can be inadvertently deployed without ejection initiation, it will be resettable without requiring removal of the seat from the cockpit.	. No quantifible aspects . Demonstrable aspects . Components requiring periodic servicing are readily accessible. . Components which can be independently deployed are simply rerigged and reset while the seat is in the cockpit.	. MIL-STD-1472B . Sound engineering	. Demonstration of accessibility of components requiring periodic servicing. . Demonstration of rerigging/resetting of inadvertently deployed components.

Table 5. (Continued)

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS: DESCRIPTION	QUANTIFIABLE ASPECTS: DATA SOURCE	QUANTIFIABLE ASPECTS: EVAL. METHOD
19. OPERATIONAL ACCEPTABILITY CONFLICTING FACTORS: 64 Drag & Inertial Forces 68 Pre-Ejection Positioning 74 Logistics BENEFICIAL FACTORS: Crew Size Personal Equipment Reach Vision Design to Cost/LCC Weight Seat Stability Seat Separation Manual Release Accessibility Ingress/Donning Egress/Doffing A/C Attitude Reliability Maintainability	Avoid crew or command resistance by emphasizing simplicity, light weight, ruggedness, and low perceptibility by flight crews.	. No quantifiable aspects . WBP system design is compatible with boarder system goals, such as low weight, ruggedness, maintainability and crew manouverability and responsiveness. . The design approach to WBP system operational acceptability does not unjustifiably compromise the primary system goal of reducing the injury and fatality rates for high speed ejections.	. Sound engineering judgement	. Solicit the opinions of active fighters pilots through demonstration and questionnaires.

Table 5. (Concluded)

CRITICAL DESIGN & EVALUATION CRITERIA

FACTOR	DESIGN OBJECTIVE & CRITERIA	QUANTIFIABLE ASPECTS: DESCRIPTION	QUANTIFIABLE ASPECTS: DATA SOURCE	QUANTIFIABLE ASPECTS: EVAL. METHOD
20. LOGISTICS CONFLICTING FACTORS: 14 Crew Size 13 Personal Equipment 15 Seat Separation 69 Ingress/Donning 70 Egress (Emergency)/Doffing 16 Drag & Inertial Forces 17 Pre-Ejection Positioning 73 Maintainability 74 Operational Acceptability BENEFICIAL FACTORS: Design to Cost/LCC Weight Reliability	To the extent possible consistent with other system objectives the WBPS will be installed on the seat, be self adjusting, will have no components requiring frequent servicing.	. If it is necessary to provide custom fitted devices for each seat occupant, critical body measurements for designing a universal customizable unit are to be used. . The design adds no new items to the personal equipment lists. . The WBPS is designed to have interchangeable items are made from standard materials available from open stock. . Permanently installed components are made rugged to minimize the likelihood of their damage.	. Sound engineering judgement	. Design review

in strap type systems should help speed the evaluation and deployment of an effective and acceptable-limb restraint system. As part of the conceptualization effort, six phases of restraint system operations were identified and defined as shown in Table 6. More than 30 different configurations of straps, cuffs and sleeves were identified and evaluated. Eight of the concepts were developed into soft mock-ups which were evaluated in manual force deployment demonstrations on an ACES B1 seat.

Subsequent to the design conceptualization effort, a design selection process was begun. The candidate limb-restraint concepts were critically evaluated against the design criteria. Six concepts were selected for recommendation for further development and testing.

DESIGN REQUIREMENTS ANALYSIS

DEFINITIONS: REQUIREMENTS, CONSTRAINTS, CRITERIA

The words requirements, constraints and criteria are frequently used interchangeably in discussions about technical programs. However, there are differences in the meaning of these words which can be useful.

The word requirement refers to the expected performance of a design relative to an implicit or explicit goal. The word constraint refers to facts or conclusions which, in effect, confine the acceptable design solution to a limited region of the potential solution space. The word criterion refers to a standard or test which may be used to judge the design's performance against its requirements.

REQUIREMENTS INTERACTION ANALYSIS

A list of factors pertinent to the windblast protection design problem is given in Table 7. A list of abbreviated design requirements, based on a study of the design factors of Table 7, is given in Table 1. Table 1 also presents, in a matrix format, all of the interactions between the design requirements. Three types of interaction are noted. These are beneficial, neutral and contradictory. Of the 180 interactions represented in Table 1, 76 are contradictory. An explanation of each of the contradictory interactions along with some possible approaches to resolution are given in Table 2.

Contradictory interaction between two requirements usually necessitates a trade-off between the requirements. Frequently, the result of a trade-off is that the design does not fully achieve the goals envisioned by either requirement. Sometimes a designer can avoid a trade-off by avoiding the

TABLE 6. PHASES OF OPERATION OF A LIMB RESTRAINT SYSTEM

PHASE	DESCRIPTION
1. Readiness	This phase encompasses storage between flights, preparation for ingress, ingress/donning, use during flight, preparation for egress, egress/doffing. The configuration of the WBPS for all of these stages of usage must be determined.
2. Capture	This phase infers to the positioning of the WBPS about the body segment to be restrained. Depending on the type of system design, capture may take place during donning, or as an automatic event during deployment.
3. Positioning	This phase refers to the events which occur during WBPS deployment which lead to the movement of an out-of-position body segment to the proper position for eventual restraint. Whatever these events are they must be compatible with normal operation of the ejection initiators and with positioning of the upper torso by the shoulder harness reel.
4. Deployment	This phase refers to the events which lead to the movement of the WBPS from its readiness configuration to the final configuration for restraints. Whatever these events are they must account for opposing friction forces and other dynamic forces which may accompany deployment path or otherwise delay deployment beyond the maximum allowable time (i.e., approximately 120 m sec).
5. Restraint	This phase refers to the deployed configuration of the WBPS which must safely react the combined aerodynamic and inertial forces which cause the limbs to move violently relative to the torso-seat mass. Load analysis for this phase should include arresting forces which may result from slack in the final deployment configuration of the WBPS.
6. Release	This phase encompasses release of the WBPS for normal and emerging egress and for seat-man separations. WBPS shielding must proceed in a manner which precludes entanglement during both emergency egress and seat-man separation.

TABLE 7. FACTORS PERTINENT TO WINDBLAST PROTECTION SYSTEM DESIGN

Factors
Aircraft Controls and Displays Interface
Aircraft Ingress/Donning, Doffing/Egress
Emergency Egress
Crew Sizing
Preejection Positioning of the Crew
Clearance During Ejection
Influence of Seat Man Stability
Extremity Protection
Seat-Man Separation
Parachute Interface
Ground and Water Landing
Reliability/Maintainability
System Safety
Design to Cost/Life Cycle Cost
Crew Encumberance and Fatigue
Psychological Aspects of Restraint System
Ejected Weight
Dynamic Environment
Cockpit Configuration Compatibility
Personal Equipment

areas in which the requirements are in conflict. If, however, the conflict is unavoidable, certain information should be available to support a judgement on the acceptability of the trade-off. First, the relative importance of the two requirements should be known, since this relationship controls the acceptability of the direction and magnitude of the trade-off. Next, in order to assess the impact of a trade-off on the level of performance of a design against a requirement, all the other trade-offs in which the two requirements are involved should be known. Finally, there should be some idea of a minimum acceptable level of performance for each requirement.

The relative importance of requirements is not normally given much consideration. But for design problems which show many contradictory interactions between requirements, relative importance must be established to provide a criterion for judging the acceptability of design performance trade-offs. The rank order importance of requirements is influenced by two main factors. These are the rank importance of the mission which the requirement goal supports, and the rank importance of the goal to the successful completion of the mission. In addition, the rank importance of a requirement may be influenced by the accessibility of the requirement goal to state-of-the-art technology or by a tendency of the requirement goal to degrade or improve system performance on other mission-important goals. Windblast protection system requirements support the missions of the aircraft, the escape system, the aircrew and the using command. Table 3 shows how the requirements are broken out under these missions, how they are ranked within the missions, and how they are ranked by overall importance across the missions.

Reorganization of the requirements interaction matrix shown in Table 1 according to the rank order of requirements taken from Table 3 gives the interaction matrix shown in Table 4. In this matrix, the row which runs diagonally up from each requirement gives its interactions with the requirements ranked higher than it in importance. Any contradictory interactions indicated in this row potentially represent a need to trade-off performance for the sake of a higher ranked requirement. The row which runs diagonally down from each requirement gives its interactions with lower ranked requirements. Any contradictions indicated in this row potentially represent trade-offs which could benefit the row's requirement. The more to the left of the matrix the greater the disparity in rank between the interacting requirements, and, therefore, the greater the justification for trading-off the lower ranked requirement to benefit the higher ranked one. The more to the right of the matrix the closer the interacting requirements are in rank, and, therefore, the greater the need to equalize the effects of a trade-off on the two requirements and the greater the justification for trade-offs which run counter to the given rank order.

PHYSICAL DESCRIPTION OF THE OPEN-SEAT EJECTION

Frames of Reference and Ejection Forces

The open-seat ejection is characterized by very high aerodynamic pressure and rapid deceleration. Within the frame of reference of the seat and its occupant, these phenomena generate apparent forces which tend to cause the occupant's limbs and head to move relative to the torso and seat. Although these apparent forces are responsible for the windblast injury problem, it is easier to comprehend their actions from an earth based frame of reference. Within the earth based reference frame, both the aerodynamic pressure and the deceleration are the interdependent results of a process by which the kinetic energy of the seat-occupant system is rapidly transferred to the air molecules in the vicinity of the seat trajectory. As the seat moves through the atmosphere, it impacts static air molecules in its path. These molecules are accelerated by their impacts in the direction of the seat motion. As the impacted molecules move away from the seat they impact new static molecules and so on. Repetition of this process leads to the formation of a pressure gradient which moves ahead of the seat-occupant system as it travels along its trajectory. The pressure gradient is created and sustained by the inertial resistance of the static air molecules which must be accelerated out of the trajectory volume and by the work performed by the seat occupant against the pressure gradient as the seat slows down. Static air molecules which are engulfed by the moving pressure gradient are accelerated forward and laterally so that they flow around the occupant and seat. This air flow, in turn, generates aerodynamic phenomena which modify the spatial shape of the pressure gradient according to the laws of aerodynamics. The spatial shape of the pressure gradient controls the distribution of pressure contours on the external surfaces of the occupant and the seat. The distribution of pressure contours, in turn, determines the net pressure forces which act on the seat, and the head, limbs and torso of the occupant.

The mass elements of the seat occupant system, the seat, the torso, the head, and the limb segments, are not rigidly connected. Therefore, if the net forces, resolved to the trajectory path and acting on each mass element, are not proportional to the mass of each element, then the elements will decelerate at different rates until the limit of articulation between the elements is reached. When a more rapidly decelerating mass element reaches the limit of its articulation, balancing forces are passed through its articulations with other mass elements until the proportionality between its net-resolved-force and its mass is uniform with those of the other mass elements. These deceleration balancing forces, which are passed through the mass element articulations, represent a windblast injury hazard to the shoulders and elbows, and especially to the knees. Wind tunnel research has

shown that the major part of the net forces on the links due to the distribution of pressure contours and the inertial response to deceleration, does not act against the direction of seat motion (References 7, 8, 9 and 11). Rather, most of the net force on the limbs acts in a lateral-outboard and an upwards direction when the seat's angles of attack are zero. This is due to the fact that the arms and the upper and lower legs dam high pressure air between themselves and the torso, seat pan, and the seat bucket, respectively. If the limbs are not restrained to the seat, they will move out laterally and upward under the influence of these forces, either until contact with seat structure is made, such as the knee contacting the lateral leg guard, or the limit of articulation is reached, such as the arm in the full backward position. At the limit of limb movement either the seat structure or the limb joints must apply to the limb an arresting force to stop the limb movement plus a force to counteract any lateral and vertical pressure forces plus a force to balance the limb's deceleration rate with those of the other mass elements. Since, at 600 KEAS, the combined lateral and vertical acting pressure forces are on the order of 600 to 1000 pounds, which is also the order of the force threshold for severe joint ligament strain injury (Reference 10), these forces represent another wind-blast injury hazard in addition to the deceleration balancing-force hazard.

Wind tunnel research has also shown that the typical open ejection seat with occupant configuration is aerodynamically unstable (References 6, 7, 8 and 9.) This is especially true in the yaw axis at high ejection speeds. As a result of this instability, the seat may yaw prior to drogue chute inflation. This potentiality gives importance to the seat occupant interface, which consists of the lap belt, the shoulder harness, and the areas of passive contact between the seat and occupant. The belt and harness give fair restraint against forward motion of the occupant. However, because of the need to accommodate a range of crew sizes, they give poor restraint against lateral movement of the occupant relative to the seat. Therefore, if the seat is yawed at the time of drogue-snatch, the seat can decelerate more rapidly than the occupant until the limit of lateral movement is reached. At the limit of lateral movement the lap belt and harness must carry a large seat body arresting load plus the force required to balance the net resolved force to mass ratios or the deceleration rates of the seat and occupant. Any limb restraint system which restricts lateral torso movement to something less than that permitted by the lap belt and shoulder harness would have to be capable of carrying similar loads without injury to the limbs. Also since the drogue riser would not be aligned with the center of gravity of a yawed seat, the drogue-snatch event causes the seat to feel a large yaw movement tending to turn the seat back toward a zero-yaw angle. Since the seat and occupant are poorly coupled in the yaw axis, the seat may reach a substantial yaw rate prior to contacting the occupant's downwind leg and shoulder. If this occurs, the knee joint could be required to carry

the lower leg inertial loads associated with the impact plus the tangential acceleration forces associated with the droguue induced yaw angular acceleration plus any deceleration balancing forces associated with the net resolved force-to-mass ratio of the lower leg. This would represent an additional windblast injury hazard to the knees. Seat back impact against the down wind shoulder would probably not present a direct injury hazard. However, the arm would feel a backward inertial force in response to such an impact. If the arm were not restrained against backward movement, the lower arm might slip out from under a loopover type restraint.

The wind tunnel study reported in Reference 11 found that the seat occupant feels about 80 percent of the total drag force for small trim angles of the seat. Therefore, in a stable ejection the seat/occupant interface is in compression with the occupant delivering force to the seat to balance their deceleration rates. When the drogue parachute inflates this situation is reversed with seat and drogue feeling most of the drag force. Therefore, after drogue inflation the seat/occupant interface is in tension with the seat delivering force to the occupant through the lap belt and harness. If the seat yaws to a large angle prior to drogue inflation, the seat/occupant interface is first put in shear, and then in tension as the seat rotates back to a zero-yaw angle. The states of compression, tension, and shear at the seat/occupant interface are illustrated in Figure 2.

The aim of the preceding discussion was first to identify the several mechanisms which generate apparent forces on the limbs during seat deceleration. These forces represent injury hazards to the limb joints and must be safely reacted by the limb restraint system, if these hazards are to be avoided. A second aim of the preceding discussion was to show that an earth based frame of reference simplifies the conceptual integration of both the force generating mechanisms and their effects, by making the simulaneity of their actions more comprehensible.

Although the simultaneity of the limb force generating mechanisms may be conceptually well understood, it is nevertheless difficult to collect quantitative data on the total forces acting on the limbs. This is due to the lace of facilities, other than sled tracks, for adequately simulating the high-speed free-body atmospheric deceleration of an occupied ejection seat. The next best option after the sled track is the wind tunnel. Wind tunnel data does provide valuable insight into the aerodynamic phenomena peculiar to an occupied ejection seat. However, it is not valid to directly extrapolate this data to obtain estimates of the actual forces which act on the limbs during the course of an ejection. There are a couple of reasons for this restriction. For one, a wind tunnel test simulates an ejection seat which traveles at constant velocity through the atmosphere. The condition of

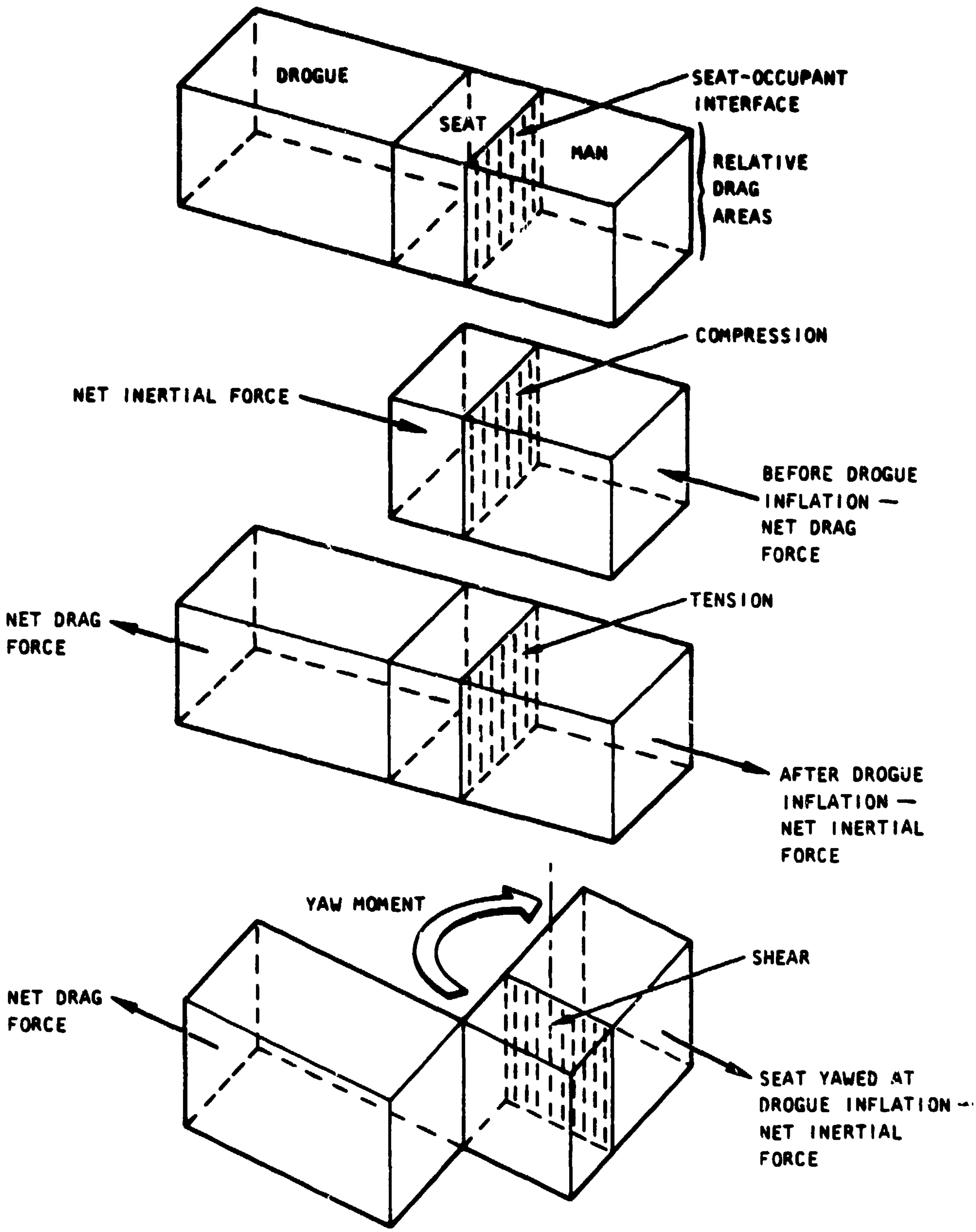


Figure 2. Impact of Drogue Inflation on Forces at Seat-Occupant Interface

constant velocity occurs only while the seat remains in the guide rails. Since a wind tunnel simulation can not account for the balance between pressure force and deceleration after guide rail separation, wind tunnel force data are prone to errors in the force components resolved to the simulated flight path.

Another reason for restricting the application of wind tunnel data follows from the fact that a wind tunnel simulation creates the artificiality of an ejection seat which maintains a stable attitude during ejection. Such a simulation can not account for the dynamic forces associated with catapult, and sustaining thruster accelerations, and with attitude rates and accelerations which are typical of in-service ejection seats. Therefore, extrapolated wind tunnel force data tend to underestimate the maximum forces acting on the limbs in an actual ejection.

Given the restrictions discussed above, wind tunnel derived limb force data may be used to obtain an understanding of the gross magnitude and direction of action of the pressure force which a limb-restraint system must safely react. Summaries of wind tunnel limb force data for the ACES II seat at various combinations of pitch and yaw attitudes are given in Reference 8, pages 34 and 35, and Reference 9, page 24. The data are given as force areas which convert to pounds force when multiplied by the dynamic pressure in pounds per square foot. A time history of the dynamic pressure for a typical high speed ejection is presented in Figure 1. The figure also shows on the same time scale the system events for an ACES II seat ejection. This figure format together with the limb force area data from References 8 and 9 facilitates the estimation of pressure force on the limbs at any point in the ejection sequence.

Seat Operations During Ejection

An acceptable limb-restraint design must be compatible with all phases of the escape system's operations. Figure 3 presents a flow chart of escape system operations and events which are pertinent to the design of a limb-restraint system.

The first level of the chart identifies four phases of system operations which are not related to ejection. These are normal and combat maneuvers, ingress and egress, restraint donnong and doffing, and emergency egress. The restraint design must sustain all aircraft maneuvering accelerations, vibrations, and occupant activities without moving from its normal stowed position to one which might restrict either the seat occupant's mobility or his internal or external vision. The design must not present any unsafe hinderance to normal ingress to or egress from the aircraft. The donning and doffing procedures required by the design must exploit

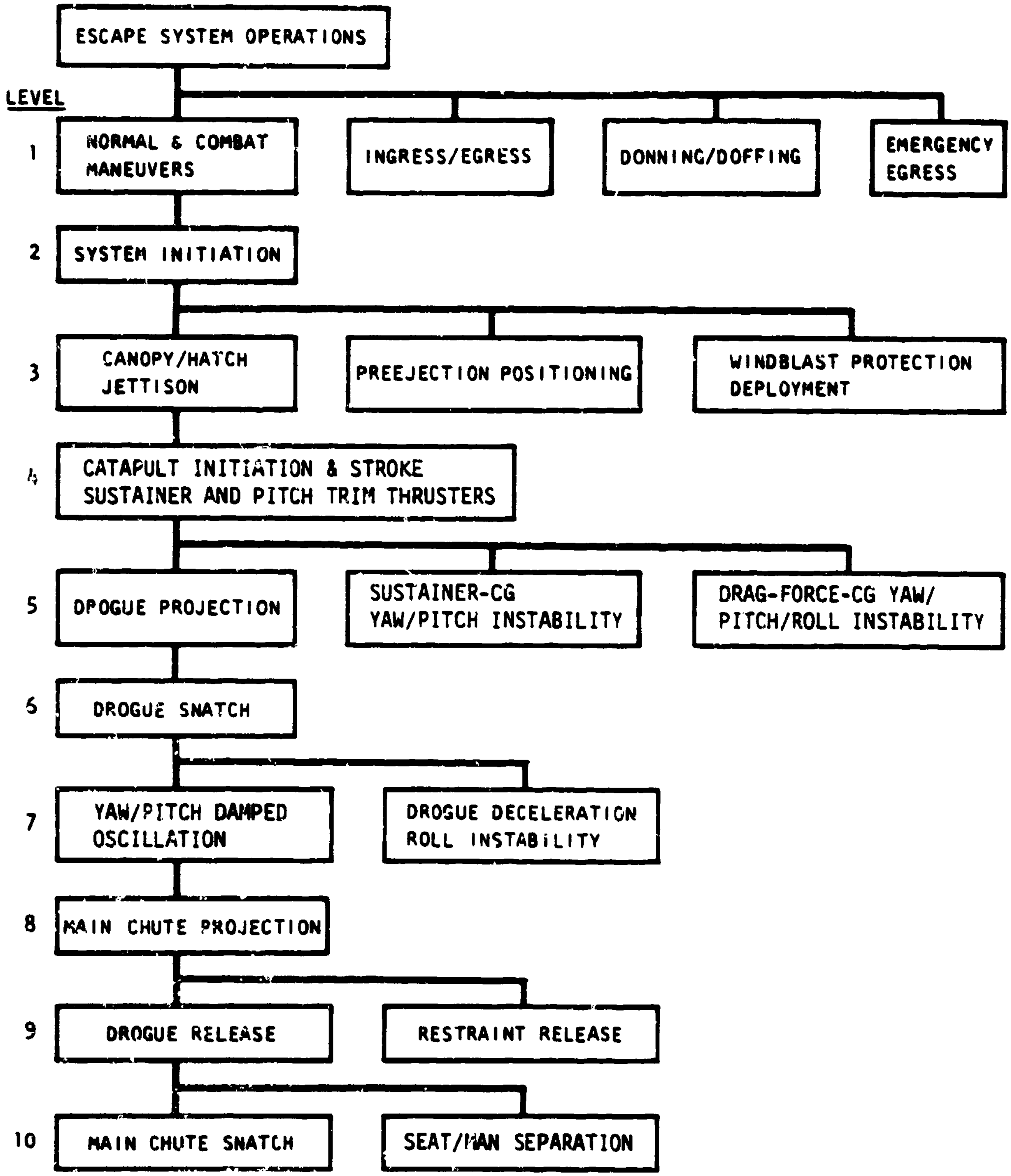


Figure 3. Flow Chart of Escape System Operations and Events

existing procedures to the greatest possible extent. The design must be compatible with single-point restraint release for rapid emergency egress and must be free of potentially unsafe encumberances to rapid egress after release.

During normal ingress or egress on the ACES II seat, the occupant must make or break seven connections, these are parachute risers to the integrated torso harness, lap belt, two survival kit straps to the integrated harness, oxygen supply and communications lead. The lap belt and survival kit connections require adjustment, bringing the number of required ingress tasks to ten. The oxygen supply and communications connections, if not manually broken, will be broken by the occupant's movement away from the seat during egress. Therefore, the number of required egress tasks is five. Upon activation of the emergency manual restraint release control (prior to ejection initiation), the parachute risers are released from the torso harness, survival kit straps are released from the survival kit, lap belt is released from the seat at both ends, and the shoulder retraction straps are released from the parachute risers. After ejection initiation, the release of the parachute risers and survival kit straps is suppressed.

The second level on the chart is system initiation. Since system initiation may be accomplished by either side-arm or D-ring controllers, the arm restraint design should be compatible with both types. The actuation of side-arm controllers can cause involuntary lateral extension of the elbows due to flexion of the occupants forearm muscles against his grip on the controller handles. Therefore, the arm restraint design must also be tolerant to lateral extension of the elbows.

The third level of the chart (Figure 3) identifies the tasks which should be accomplished prior to catapult ignition. Canopy removal may begin immediately upon escape system initiation. In this case, the seat and occupant will be exposed to turbulent windlast within milliseconds following actuation of the ejection controller. The limb restraint design, particularly that for the arms, should be tolerant to windblast exposure during its transition from the stowed to the deployed configuration. The time required for canopy removal generally decreases with increasing dynamic pressure and, consequently, with increasing risk of windblast injury. Therefore, the limb restraint design must be capable of very rapid deployment (on the order of 130 milliseconds), if additional ejection sequence delays are to be avoided.

Initiation immediately after battle damage under high g-loads or command initiation are situations which present significant probabilities for the occupant being out of the normal ejection posture. Therefore, the restraints

design must be configured to apply appropriate positioning forces to out of position limbs. Since the torso may also be out of position at initiation, the limb-restraint design must be capable of applying effective limb positioning forces to the arms while the shoulder harness is retracting the torso to the seat back.

Deployment of the windblast protection restraints must begin at escape system initiation and should be complete before catapult initiation. Limb restraint deployment must be compatible with the configuration of seat and cockpit hardware and with the occupant's personal equipment.

The fourth level on the flowchart (Figure 3) is catapult initiation. Catapult initiation may be linked to canopy thruster separation and, therefore, may occur as early as 120 milliseconds after system initiation. During the catapult stroke, which lasts about 200 milliseconds, the occupant will experience acceleration loads in the neighborhood of 14 g parallel to the seat roller plane. Since sucn loads may be near or beyond the population threshold of injury to the spinal column, the arm restraints must not add an additional force component to these loads. If the arm-restraint design aims to complete deployment during catapult stroke, the design's deployment kinematics must be compatible with both catapult acceleration loads and dynamic pressure forces. If the axis of a lower leg is behind a plane which is parallel to the roller plane and passes through the knee, the catapult acceleration load on the lower leg will create a movement at the knee which will cause the lower leg to accelerate forward away from the seat. Therefore, the leg restraint design must be capable of arresting such forward motion while applying positioning forces to the lower leg. Since the lower leg is shielded from the windblast for at least a part of the catapult stroke, leg-restraint design should save weight be exploiting seat motion to generate leg-restraint deployment forces. At catapult separation, the sustainer rocket and the pitch trim rocket (ACES II seat) are ignited. The sustainer rocket continues the acceleration of the seat away from the aircraft. If the seat's yaw angle of attack is small, the sustainer also tends to resist deceleration along the seat's trajectory. This would temporarily slow the reduction of dynamic pressure, which would otherwise result from deceleration. It also temporarily reduces the inertial relief from dynamic pressure forces, which the deceleration loads would provide for the limbs.

In regard to dynamic pressure forces on the limbs, the period during which the seat separates from the aircraft is the most critical. If control of the limbs is not established by this time or it is lost during initial windblast exposure, injury at high speed is almost unavoidable. Level 5 of the flowchart identifies the events and phenomena which occur between seat separation from the aircraft and inflation of the drogue chute. As soon as the drogue chute compartment clears the aircraft structure, the drogue is

projected out behind the seat. While the drogue is deploying, the seat-occupant system may experience destabilizing force moments generated by two different mechanisms. One mechanism is driven by the vertical and/or lateral offset of the center of gravity (CG) of the seat-occupant system from the line-of-action of the sustainer rocket. A vertical CG offset creates a pitch moment. A lateral CG offset creates compound yaw and roll moments because of the nonorthogonal relationship of the thrustline to the yaw and roll axes. The other destabilizing mechanism is controlled by the instantaneous offset of the CG of the seat-occupant system from the line-of-action of the net pressure or drag force on the seat. In turn, the line-of-action of the drag force is controlled by aerodynamic properties of the seat-occupant system in all of its attitudinal positions. Aerodynamics properties of the seat-occupant system are, in turn, the product of the special configuration of the external surfaces of the seat and its occupant. Finally, the surface configuration of the seat-occupant system is significantly influenced by the occupant's size and posture and by the equipment he wears. Since this chain of control ends at uncontrollable attributes of the occupant, open-ejection seats are especially prone to destabilization by this mechanism. Up to the limits of its capacity, the gyroscopically-stabilized pitch-trim rocket counteracts the combined pitch moments due to the CG offsets from the sustainer-thrust and drag-force lines-of-action. Since the ACES II seat has no capacity to counteract the combined yaw and roll moments due to these offsets, the seat tends, especially at high dynamic pressure, to yaw and roll prior to drogue chute inflation.

The sixth level of the flowchart (Figure 3) is the drogue snatch event. This event begins with the first full inflation of the drogue chute and ends with the first passage of the seat through the zero-yaw angle of attack. The drogue is attached to the seat by a riser which branches into a two-legged yoke before reaching the seat. The yoke ends are attached to either side of the back of the seat at the level of the seat-occupant CG. Since the yoke legs are fixed in length, the leg opposite the yaw direction carries the full drag force of the drogue chute when the seat is yawed. This results in a large yaw moment on the seat. At first, this moment is resisted by the yaw-angular momentum of the seat. Therefore, the seat and occupant experience a large transient lateral deceleration. The continued action of drogue force on the seat causes a large yaw-angular acceleration of the seat which rapidly arrests and reverses its yaw-angular velocity. As was mentioned previously, this rapid reversal of seat motion can lead to impacts of the seat against the occupant due to the weak yaw coupling between them. The large yaw-angular acceleration may also cause the limbs to feel large tangential acceleration loads which tend to dislodge the limbs from their proper positions and may be additive to the pressure forces also tending to dislodge the limbs.

If the seat has rolled as well as yawed prior to drogue snatch, as would be expected due to the presence of a large drag force roll moment opposite in sign to the yaw direction (Reference 8, page 68), the taut leg of the drogue yoke may also generate a substantial roll moment on the seat in the same direction as the drag-force roll moment. These combined roll moments can generate large roll velocities in the seat-occupant system Such roll velocities would generate radial acceleration loads on the limbs which would add to the other forces and loads on the limbs which tend to dislodge them from their proper position and pull them away from the torso.

Level 7 on the flowchart identifies events which occur after drogue snatch and before main-chute projection. As indicated above, forces which act during the drogue-snatch event can generate yaw and roll velocities in the seat-occupant system. If the seat were yawed prior to the drogue snatch event, the seat would be yawed back toward a zero yaw angle of attack by the force in the drogue riser. As the seat passes through zero yaw angle, the drogue load transfers from one leg of the riser yoke to the other. This causes a rapid reversal of the yaw moment on the seat which arrests and reverses the seat's yaw velocity. The seat may go through several yaw velocity oscillations of decreasing magnitude before the seat stabilizes at a zero yaw angle. Since inflation of the drogue chute greatly increases the drag area of the seat, the seat tends to decelerate more rapidly than the occupant. Separation of the occupant from the seat is prevented by the application o' backward acting loads to the occupant through the shoulder harness and lap belt. Since, in this condition, the yaw coupling between the seat and occupant is especially weak, the relative motion between the seat and occupant would be damped, asynchronous, yaw oscillations. Any limb-restraint design which increases the yaw coupling between the seat and occupant must be able to demonstrate that the coupling forces applied to the limbs do not contribute excessively to adverse loading of the limb joints during yaw stabilization. An alternative design approach would be to avoid increasing the yaw coupling between the seat and occupant. The oscillatory relative motion between the seat and occupant during yaw stabilization may also threaten limb-restraint designs which are dependent on friction to maintain the proper position of the limbs and/or restraints. If the needed friction forces change magnitude during an oscillatory cycle, the limb or restraint may progressively shift position until the limb is freed or the restraint becomes ineffective in regard to the prevention of injurious forces or displacements in the limb joints. Since the drogue chute is not capable of directly stabilizing the seat against any roll velocity which the seat might have acquired during the drogue-snatch event, the seat may continue to roll during drogue deceleration. However, other indirect mechanisms, such as uneven loading in the legs of the drogue riser coupled with a nonzero pitch angle, may cause roll moments during drogue deceleration. It is not known whether such moments tend to stabilize, destabilize, or act randomly in regard to

seat-roll behavior.

Level 8 on the flowchart (Figure 3) is the main-chute projection event. Main-chute projection is accomplished by the detonation of a mortar charge under the main parachute pack located behind the headrest (ACES II seat). As the parachute pack moves away from the seat, the riser slack loops are pulled out from behind the back pad. The risers then tension against the occupant's harness and against the seat through the torso retraction straps which are connected to the risers. The tension in the risers pulls the main chute out of its pack as the pack continues to separate from the seat. Primary restraint release is delayed for 0.25 second after main-chute projection. Therefore, head- and arm-restraint designs must be compatible with tensioning of the riser straps prior to primary restraint release. The movement of the main-chute pack or the withdrawal of the riser slack loops may be exploited by restraint designs to release arm- or head-restraints prior to primary restraint release. The acceleration of the main-chute pack away from the seat creates a small pitch moment about the seat-occupant CG. Also the separation of the parachute from seat lowers the seat-occupant CG. Therefore, depending on the pitch trim of the seat, the drogue may also apply a small positive pitch moment to the seat after main-chute projection. The combined action of these moments may cause the seat to acquire a positive pitch rate by the time the drogue is released 0.15 second after main-chute projection.

Levels 9 and 10 on the flowchart identify the events which occur between main-chute projection and seat/man separation. These are drogue release, restraint release, main-chute snatch and seat/man separation. Drogue release occurs 0.15 second after main-chute projection. At the release of the drogue, the seat loses the pitch and yaw stability which the drogue provides. Therefore, the pitch and roll velocities which the seat might have at drogue release can continue after drogue release. In ejection tests, some seats, which are rolling at the time of drogue release, have been observed to undergo a maneuver in which the seat pitches back and yaws subsequent to drogue release. All of the mechanisms which drive this maneuver are not known. The maneuver has been observed to lead to the seat being in a yawed relation to the main-chute risers at main-chute snatch. In addition, the form of this maneuver allows the riser furthest from the main chute to move in front of the headset and behind the occupant's head. In this configuration, the occupant's head and neck would carry the full main chute snatch load. Head restraint designs must be capable of preventing this situation or of reacting the riser load into the seat. Primary restraint release occurs 0.25 second after main-chute projection. Arm and leg restraints must be released no later than primary restraint release. After the arm and leg restraints are released, they must allow the seat to move away from the man without interference. In particular, it must be nearly

impossible for the restraints to catch on the man's body or personal equipment. Furthermore, the limb restraint design should have this capability for unstable as well as stable seat/man separations; that is, separations in which roll and yaw velocities as well as pitch velocities are present.

Implications for Windblast Protection

The primary goal of a windblast protection system is to prevent limb dislodgement during an ejection. However, achievement of this goal alone would not automatically preclude windblast induced limb injuries because, even when restrained against displacement, the limbs may be vulnerable to injuries to their joints. This potential vulnerability arises from the limited capacities of the knee, shoulder, and elbow joints to carry tension, torsion, bending, and shear loads without sustaining serious strain injuries to the joint ligaments. Therefore, an acceptable limb-restraint design not only must react to the apparent forces which tend to dislodge the limbs from their proper positions but also must do this in a manner which holds the levels of the loads carried by the limb joints below the threshold for serious strain injury. To ensure that this criterion is met, the designer and evaluator should know the configuration and functioning of the knee, shoulder, and elbow joints, and in particular, the special vulnerability of each joint in regard to its potential loading during an ejection. Toward this end, the rest of this section presents short discussions of the special vulnerabilities of the knee, shoulder, and elbow joints, and of the spine as they relate to the windblast protection design problem.

The Knee Joint

The vulnerability of the knee joint arises both from the configuration of its interior and exterior ligaments when flexed and the peculiar aerodynamic and inertial forces acting on the upper and lower legs during windblast exposure. The internal ligaments of the knee are located in the center of the joint behind the patella (knee cap). When the knee is extended, the internal ligaments form an "X" in the plane of articulation between the articular heads of the femur (thighbone) and tibia (shinbone). (See the diagram on Figure 4.) These crossed ligaments, known as the external (or anterior) and internal (or posterior) cruciate ligaments, force the rolling articulation which is characteristic of the knee joint. The anterior cruciate ligament forms a link between the anterior border of the head of the tibia and the posterior border of the head of the femur. The posterior cruciate ligament is located on the inside of the anterior cruciate and links the posterior border of the tibia, to the anterior border of the femur. When the knee is flexed, the anterior cruciate ligament carries loads which tend to separate the knee joint along the axis

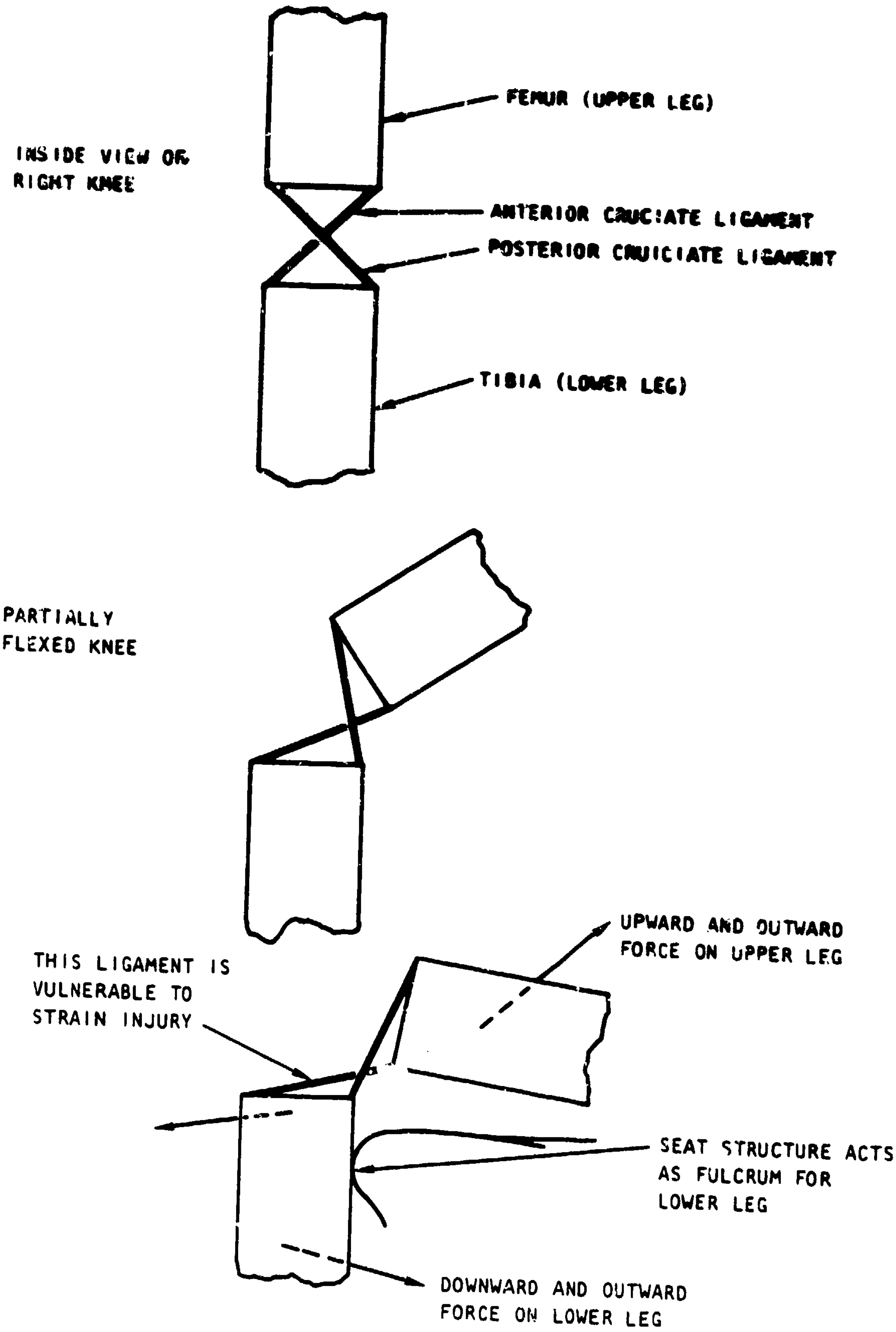


Figure 4. Internal Ligaments of Knee

of the femur, while the posterior cruciate, which is much stronger, carries loads which act along the axis of the tibia.

Windblast forces can act to push the upper leg up, out, and back, while the forces on the lower leg primarily push it back and out. Together these forces tend to flex the leg over the forward edge of the seat pan. If the seat pan depth is greater than the occupant's buttock-popliteal length (upper leg length) or if the upper leg is lifted off the seat pan, the forward edge of the seat pan may act as a fulcrum for the lower leg and, thereby, generate forces which act to separate the bones of the knee and load the knee joint ligaments, especially the anterior cruciate. (See Figure 4.)

The exterior ligaments of the knee prevent hyperextension and lateral bending of the joint. The most vulnerable of the exterior ligaments is the medial collateral ligament located on the inner or medial side of the knee. This ligament offers the primary resistance to lateral outward bending of the lower leg at the knee joint. When the knee is flexed the lower leg can be rotated to the outside only when the femur is allowed to rotate at the hip joint.

The pressure forces which act on the upper and lower leg tend to push the leg out laterally. Restraints designed to react these forces must not be positioned where they might generate excessive loads in the medial collateral ligament. For example, if the lateral restraint for the lower leg were located near the knee joint, the restraint could act as a fulcrum about which the lower leg would pivot. (See Figure 5.) In such a case, the head of the tibia would be rotated inward and downward. This motion would place the medial collateral ligament in tension, and would, therefore, greatly increase the risk of strain injury to this ligament.

The medial collateral ligament is also vulnerable to torsional displacements of the tibia at the knee joint. The best available design limits for tibial rotation are 17.5-degrees internal and 20-degrees external (Reference 10). Lower leg-restraint designs, which are capable of applying torsional forces to the lower leg as it moves within the limits of the restraint, must be able to demonstrate that torsional forces are not applied to the lower leg beyond the torsional displacement limits for the tibia.

The Shoulder Joint

The shoulder is a ball-and-socket type joint. The bones entering into its formation are the head of the humerus (upper arm), which is received into the shallow glenoid cavity of the scapula (shoulder blade)

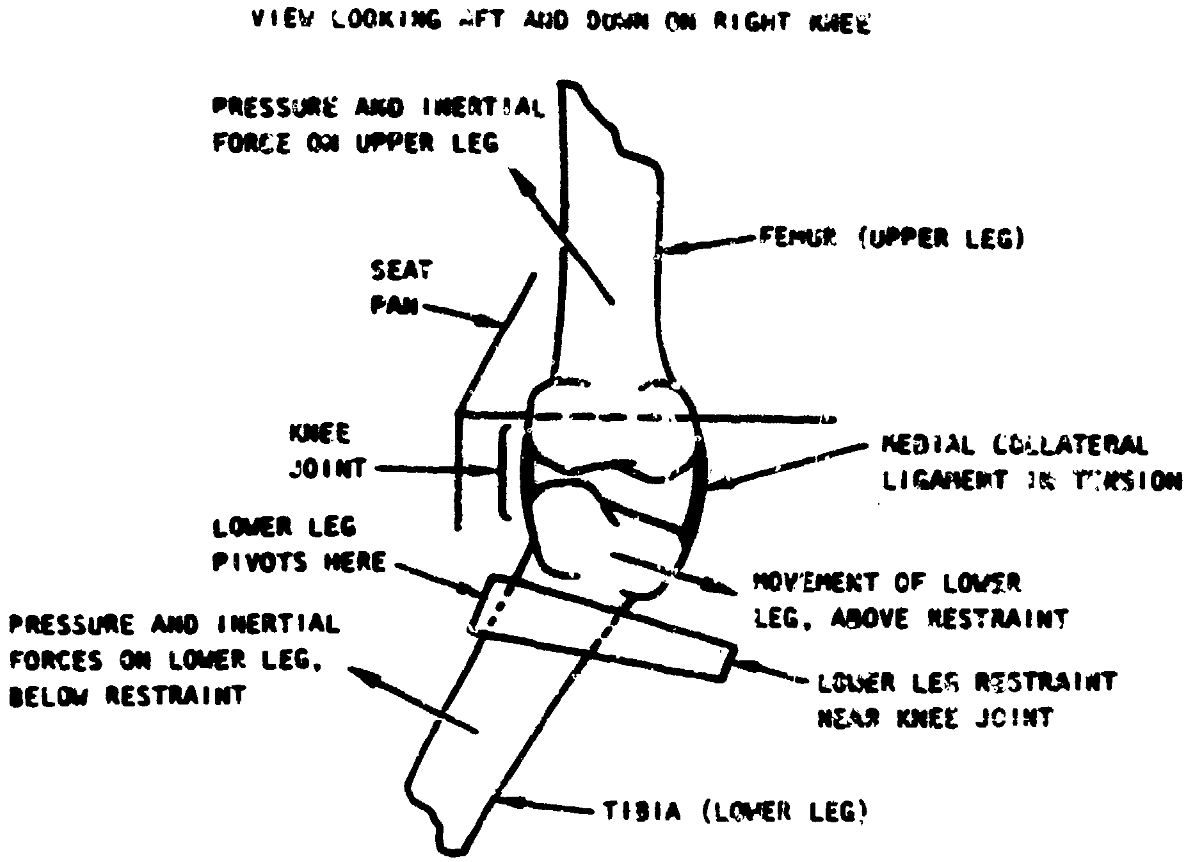


Figure 5. Effect of Lower Leg Restraint Positioning on Medial Collateral Ligament

- an arrangement which permits very considerable movement, while the joint itself is protected against displacement by the tendons which surround it and by atmospheric pressure. The ligaments do not maintain the joint surfaces in apposition, because when they alone remain the humerus can be separated to a considerable extent from the glenoid cavity, their use, therefore, is to limit the amount of movement...

"Owing to the construction of the shoulder joint and the freedom of movement which it enjoys, as well as in consequence of its exposed situation, it is more frequently dislocated than any other joint in the body. Dislocation occurs when arm is abducted, and when, therefore, the head of the humerus presses against the lower and front part of the capsule (ligament), which is the thinnest and least supported part of the ligament. The rent in the capsule almost invariably takes place in this situation, and through it the head of the bone escapes." (Reference 12).

The vulnerability of the shoulder joint to forces which tend to push the head of the humerus against the lower forward section of the joint capsule creates important constraints on arm restraint designs. For example, if, in order to restrain the arm against flailing, force is applied to the wrist in a forward direction, the upper arm will be susceptible to abduction (rotation away from the body) by the pressure forces which act on the arm. If the upper arm were so abducted and if the seat were to yaw prior to drogue snatch (both are likely events), the action of the pressure force on the arm would shift from lateral-outboard to lateral-inboard resulting in a large inward force at the head of the humerus. This force would be combined with the forward acting inertial force on the arm resulting from the rapid yaw realignment of the seat by the drogue-snatch event. The combined pressure and inertial forces could generate a resultant force acting at the head of the humerus in the general direction of maximum vulnerability to shoulder-joint-displacement injury. Therefore, an acceptable arm-restraint design must apply forces to the upper arm to prevent its abduction by pressure or inertial forces. Furthermore, the upper arm-restraint must not be located near the shoulder joint, since such restraint could serve as a fulcrum by which abducting forces acting below the restraint would be transformed into dislocating forces at the head of the humerus.

The Elbow Joint

The elbow is a hinge type joint which controls the articulation between the humerus (upper arm bone) and ulna (forearm bone). The articular surface of the humerus is rounded - convex with a medial groove in the plane of articulation. The head of the ulna is a concave socket of about 90° of arc. This socket has a medial ridge which interlocks with the medial groove on the humerus.

The socket of the ulna is formed by two bony processes. The posterior or olecranon process covers the back of the joint when the elbow is extended. The anterior or coronoid process covers the front of the joint when the elbow is flexed.

The elbow joint is well protected against lateral dislocation of the bones by the interlocking ridge and groove and by strong lateral ligaments and muscle tendons which act to hold the bones together and keep them interlocked. However, by comparison, the elbow joint is quite vulnerable to forward and aft dislocations. As shown in Figure 6, when the forearm is extended, the ulnar socket is open at the front, and the posterior ligament at the back of the joint is slack. Therefore, there is relatively little resistance to backward dislocation of the ulna off the humerus when the elbow is extended. When the elbow is flexed, the ulnar socket is open at the back, and the anterior ligament at the front of the joint is slack. Therefore, there is relatively little resistance to forward dislocation of the ulna off the humerus when the elbow is flexed.

The flexed elbow is vulnerable to forward dislocation when forces act backward on the humerus and downward along the axis of the ulna. The extended elbow is vulnerable to backward dislocation when forces act forward on the humerus and backward on the ulna.

The forward dislocation vulnerability of the elbow is a critical constraint on windblast protection designs, because the elbows are flexed after operation of side-arm or high D-ring controllers (one requirement for forward dislocation), and because most of the pressure force acts perpendicular to the humeral axis and away from the ulna while most of the resistive force of the hand grip acts parallel to the ulnar axis and away from the humerous (the other requirement for forward elbow dislocation).

This situation is worsened by the high probability that the occupant's upward pull on the controller causes his triceps muscle to be fairly loose. If the triceps were tensed, it would offer some protection against forward dislocation of the elbow.

This analysis suggests that forward elbow dislocation should be a frequently occurring ejection injury. However, experience has not confirmed this expectation. It is reasonable to speculate that the resolution of this discrepancy lies in another discrepancy between experience and expectation, namely, that grip strength is less effective at preventing arm flail than expected. Both discrepancies would be explained, if a nervous reflex exists which loosens the grip when elbow dislocation is imminent.

The forward and backward dislocation vulnerabilities of the elbow impose implicit constraints on arm-restraint design. Simple restraint of the arm at the wrists, for example, is unacceptable, because it cannot

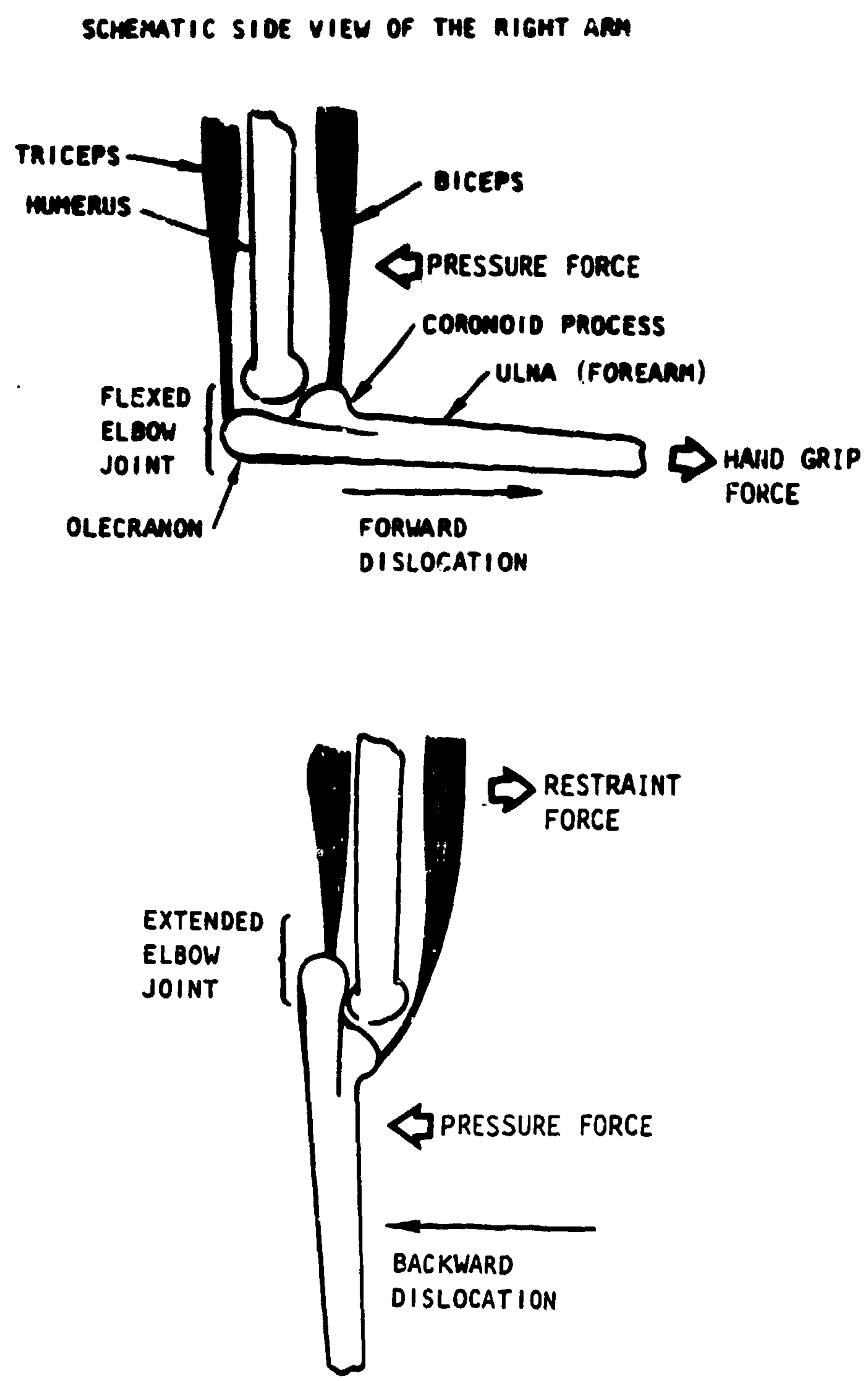


Figure 6. Dislocation Vulnerabilities of Elbow

prevent forward elbow dislocation. If the wrist is restrained, restraint must also be provided for the upper arm in a manner that will react backward acting forces on the humerus.

The elbow's vulnerability to backward dislocation also constrains the design of arm restraints based on the "in-trail" arm position. If forward-acting restraint is provided to the upper arm, then similar forward-acting restraint must be provided to the forearm to prevent hyperextension or backward dislocation of the elbow.

The Spinal Column

Another critical constraint on strap-based limb-restraint designs is derived from the vulnerability of the vertebrae of the spinal column to compression fractures during catapult acceleration or drogue-opening shock. Vertebral fractures usually occur when the spine bends before or during the application of a compressive force because bending causes edge loading of the vertebrae rather than uniform loading across the intervertebral discs. Therefore, strap-type arm restraints are constrained to not introduce forces on the torso which would result either in undesirable bending moments or additional compressive loads at the spine.

The criticality of this constraint is recognized when one observes that strap type restraint designs may include a phase wherein the straps are retracted and snubbed. If this process continues during catapult acceleration, the straps may be retracted and snubbed against the dynamically slumped position of the arm or torso. In this case, when the torso rebounds from the catapult stroke, it would be arrested by the snubbed arm restraints and could result in significantly larger bending moments or compression loads at the spine than would be expected from a purely static analysis.

DESIGN AND EVALUATION CRITERIA

Table 5 presents a compilation of design and evaluation criteria developed from the requirements interaction analysis presented in Tables 1 and 2. The compilation has a section for each of the 20 requirements listed in Table 1. Each section contains a summary of the conflicting and beneficial interactions of its requirement with the other 19 requirements. A number in front of each conflict refers to an explanatory note in Table 2. Each section also identifies the design objectives and criteria pertinent to its requirement, describes the quantifiable aspects of the design objectives and criteria, identifies sources of quantitative data, and suggests evaluation methods.

DESIGN CONCEPTUALIZATION

The effort to develop windblast protection design concepts was heavily influenced by the requirements interaction analysis summarized in Table 4 In relation to this analysis, many previous windblast design solutions appear either to be deficient in their performance against one or more of the first three requirements in Table 4 and/or to represent unacceptable tradeoffs of performance among these requirements. For example, protection schemes dependent on diversion of airflow away from the limbs are either too heavy or overly sensitive to aircraft and seat attitude or both. Schemes which depend on seat stabilization or passive limb-restraint are similarly disadvantaged. Protection schemes which feature active restraint of the limbs against the aerodynamic and inertial ejection forces offer the best potential for resolving the conflicts between the requirements for low weight, adequate protection, and insensitivity to aircraft and seat attitude.

The operation of an active limb-restraint system may be divided into six phases which may or may not overlap. These phases are readiness, capture, positioning, deployment, restraint, and release. A definition for each of these operational phases is presented in Table 6.

Evaluations of previous approaches to active limb-restraint design were begun be determining how each approach addresses the problems peculiar to each of the six phases of system operation. Then each approach's performance against the windblast protection design requirements was assessed by comparing its implicit performance tradeoffs with the tradeoff criteria contained in Table 4. This exercise provided a large conceptual base which was cross organized by specific functional problem areas and performance tradeoff acceptability.

Working from this conceptual base, we developed six limb restraint concepts. These include three arm restraint concepts and three leg restraint concepts. Sketches of these concepts are presented in Figures 7 through 13, along with the following verbal descriptions of their deployment sequences. Multiple candidates are presented for both the arm and leg restraints because they are thought to be close enough in potential overall performance to warrant carrying all six into prototype evaluations.

CONCEPT ONE

This concept is for arm protection using a strap retention system which is integral with the seat and harness. Normal ingress and egress from the aircraft are all that is required to have the system in the prepared state. Power for the system could be either seat motion or an aircraft mounted retraction reel. This concept is illustrated in Figure 7 and the following is the six-step deployment sequence:

a. Slack in the retracting-strap (15) is taken up through the snubber (10) the belt-ring (13) and the rise-ring (16) until the shoulder-loop (3) tensions against its tacking to the upper corner of the seat back pad (2).

b. Force resulting from tension in the retracting-strap (4 and 15) causes the riser-ring (16) to break open. The resulting slack is taken up until the retracting-strap again tensions against the back pad (2).

c. The break cord which holds the retracting-strap to the back pad (2) is broken by the force exerted by the strap. The resulting slack is taken up until the retracting-strap-terminal-ring (6) tensions against the restraining-strap (14).

d. As the retracting-strap draws its terminal-ring (6) around the arm, the lower side of the restraining-strap (7) is drawn up to the ring and passes through it and is thereby positioned for restraining the upper arm.

e. As the retracting strap continues to draw its terminal-ring (6) toward the belt-ring (13), the lower side of the restraining-strap is pulled over the lower arm. The restraining-strap eventually tensions against the aft-riser-support-ring (5), the retracting-strap-terminal-ring (6) and the restraining-strap-anchor-on-the-side-of-the-seat-bucket (11 and 12).

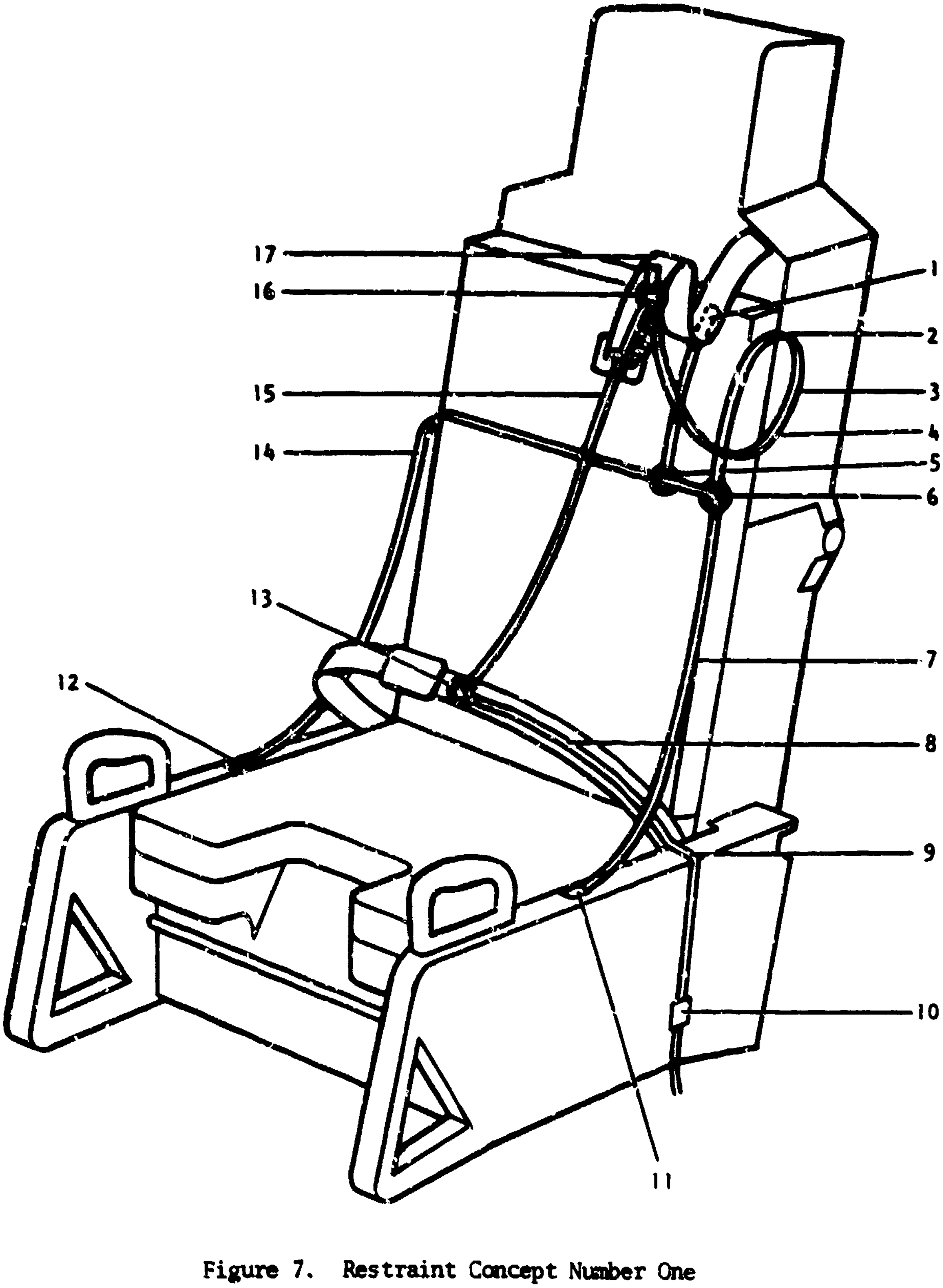


Figure 7. Restraint Concept Number One

f. At seat-man separation the snubber/cutter (10) cuts the retracting-strap. As the seat falls away from the man, the retracting-strap is drawn through the belt-ring (13) by the restraining-strap (7) and terminal-ring (6). When the cut end of the retracting strap passes through the ring, the occupant is freed from the restraint strap.

CONCEPT TWO

Concept two is also a strap design for arm protection. However, it differs significantly from concept one in that the wrist is positively held by the system and requires that this connection be made and broken for each wrist during normal ingress and egress. In addition, the shoulder loop (items 3 and 4 on Figure 8) must be attached to a keeper on the upper arm of the flight garment. The following is a step-by-step deployment cycle for concept two, as illustrated on Figure 8:

a. The retracting strap (8) is pulled through the snubber/cutter (11) and the lap-belt-ring (10). The retracting-strap-terminal-loop (4), in turn, pulls the restraint strap (3) through the upper arm keeper (not shown) until the restraint-strap-slack-loop (6) is consumed.

b. The retracting-strap-terminal-loop (4), which is tacked to the restraint strap (3) with break cord, tensions the restraint strap (3) against the upper arm keeper (not shown) until the keeper rips open. As the retracting strap (8) is pulled through the lap-belt-ring (10), the restraint-strap (3) is drawn into a taut loop around the upper arm. This loop is prevented from sliding down off the upper arm by the support ring (2) located behind the back and anchored by a short length of strap to the seat back (1).

c. When the restraint strap (3) tensions on the upper arm, the retracting-strap-terminal-loop (4) breaks its tacking. This allows the terminal loop (4) to slide down the restraint strap (7).

d. When the terminal loop (4) reaches the lap-belt-ring (10), it slips through the ring, pulling the restraint strap with it.

e. As the restraint strap (7) is pulled through the lap-belt-ring (10), the wrist loop (9) is pulled to the lap-belt-ring (10).

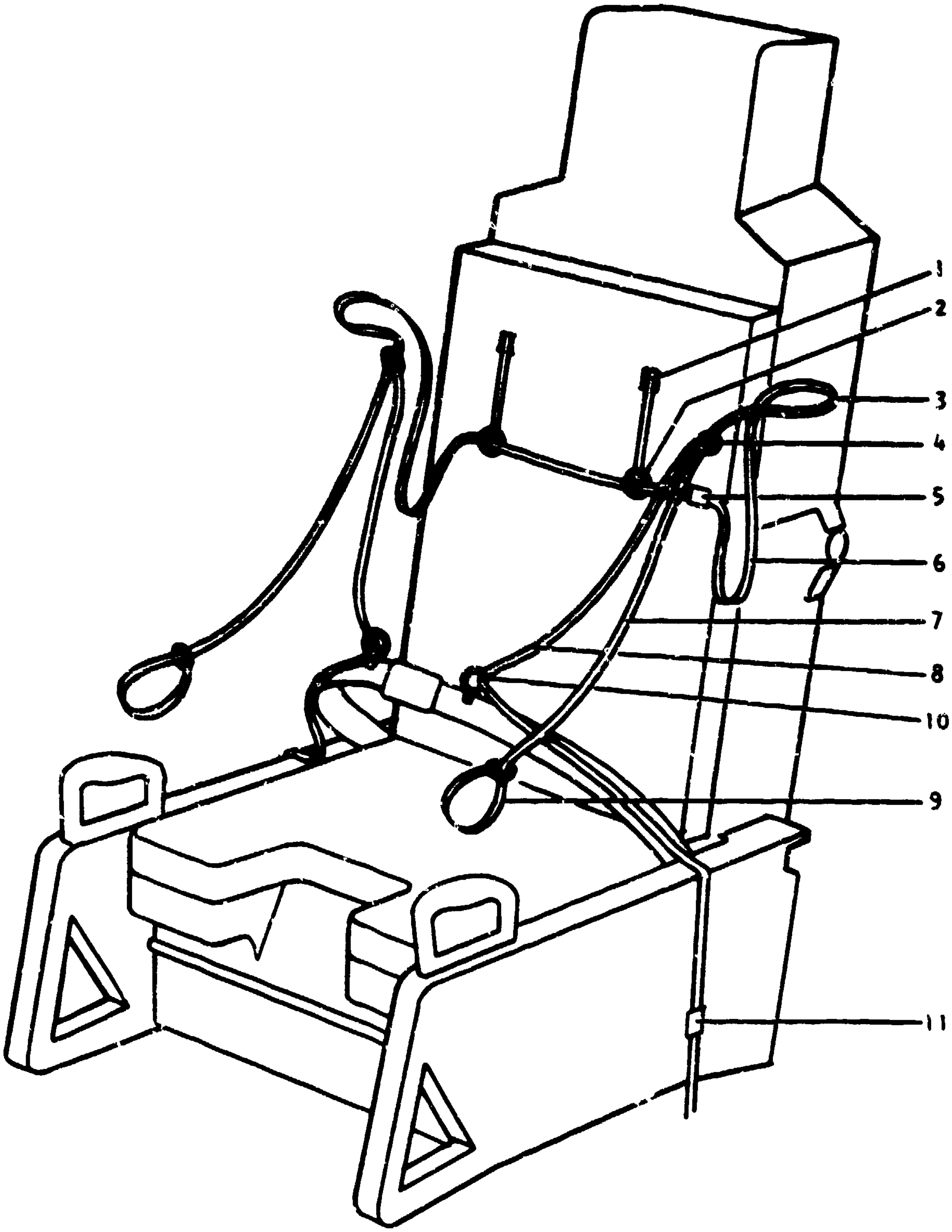


Figure 8. Restraint Concept Number Two.

f. Arm restraint is complete when the wrist loop (9) reaches the lap-belt-ring (10).

g. At seat-man separation or emergency egress, the restraint strap (6) is cut by explosive cutters (5) mounted in the back pad. The retracting strap (7) is cut by the snubber/cutter (11).

CONCEPT THREE

Concept three is also an arm-restraint design, but is significantly different than concepts one and two. Concept three consists of a high strength sleeve with deployment straps rolled up with it. The rolled-up sleeve is attached to the main parachute riser via an epaulet and is left on the seat during normal ingress and egress, the arm simply being inserted through it while entering the harness. During deployment it is rolled down the arm and essentially suspends the arm in a cylinder anchored at the top and forward outer edges of the seat. Figure 9 illustrates the concept with sequential deployment as follows:

a. The deployment strap (8) is pulled through the snubber/cutter (9) and the controller-ring (10). When the slack between the controller-ring (10) and the emergency egress cutter (6) is consumed, the deployment strap is pulled out of the cutter (6). This allows the mobility-slack-loop (7) to be consumed.

b. Tension in the deployment strap (8) is passed through the deployment-strap-branch (5) and the unrolling straps (4 and 12) to the rolled sleeve-cuff (11). Since both the sleeve and unrolling straps are rolled up on a stiff foam rubber ring, this tension causes the sleeve to unroll down the arm.

c. Concurrent with event (a), the support strap (2) is pulled through the support ring (1) and the support snubber/cutter (3). After the support-strap-slack-loop (2) is consumed, the support strap tensions against the top of the sleeve. The top of the sleeve is also supported by a cloth yoke (13) suspended from the parachute riser (14), but the attachment of the yoke to the riser is weak and may release during sleeve deployment without consequence.

d. Arm restraint is complete when the sleeve has completely unrolled.

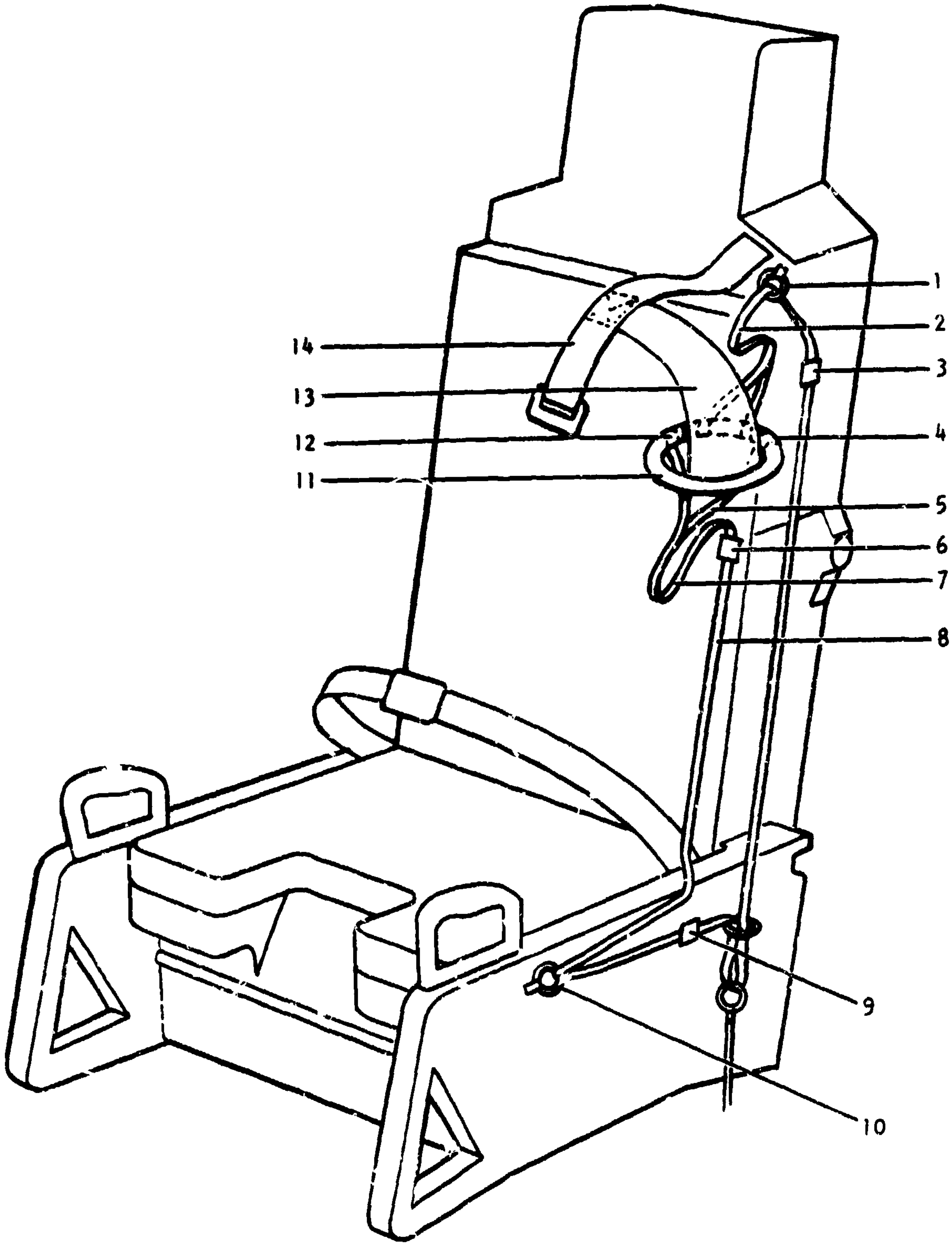


Figure 9. Restraint Concept Number Three.

e. At seat-man separation the support strap and deployment strap are cut at their respective snubber/cutters (3 and 9). This releases the seat from the sleeve.

f. At emergency egress, the emergency egress cutter (5) severs the deployment strap. The support strap is severed by its cutter (3). The sleeve support yoke (13) tears off the riser (14) during egress.

CONCEPT FOUR

This is a leg-restraint concept which is retained as an integral part of the ejection seat. It consists of a high strength upper and lower leg shroud for each leg which would be pulled tight during initial seat travel. Ingress would require the crew member to drape the devices over his legs and connect the make-and-break fitting (item 10 on Figure 10) at the forward edge of the seat pan. Figure 10 is an illustration of the concept which correlates to the following deployment sequence:

a. As part of the ingress procedure, the occupant pulls the upper and lower leg-restraint-flaps (2 and 6) over the leg, and inserts the flap-anchor-ring (11) into the snap-hook (10) at the center of the forward edge of the seat pan.

b. During the catapult stroke, the lanyard-ring (8), which is attached to the cockpit floor, pulls the tensioning strap (7) through the inner snubber/cutter (9) and the outer snubber (12).

c. The tensioning strap (7) pulls the snap hook (10) and the flap-anchor-ring (11) down to the inner snubber/cutter (9). This collapses the sleeve between the snap hook (10) and the snubber/cutter (9) and thereby precludes the release of the barrel connector which holds the snap hook (10) to the tensioning strap (7).

d. The tensioning strap (7) is pulled through the outer snubber (12), thereby consuming the mobility-slack-loop (13). The tensioning strap then pulls slack through the hem of the outer border of the lower-leg-flap (5). This snugs the lower-leg-flap (6) over the lower leg.

e. Having consumed all of the free slack, the tensioning strap (7) pulls against its anchor at the back of the seat pan (1). The taut tensioning strap pulls down on the fabric channel

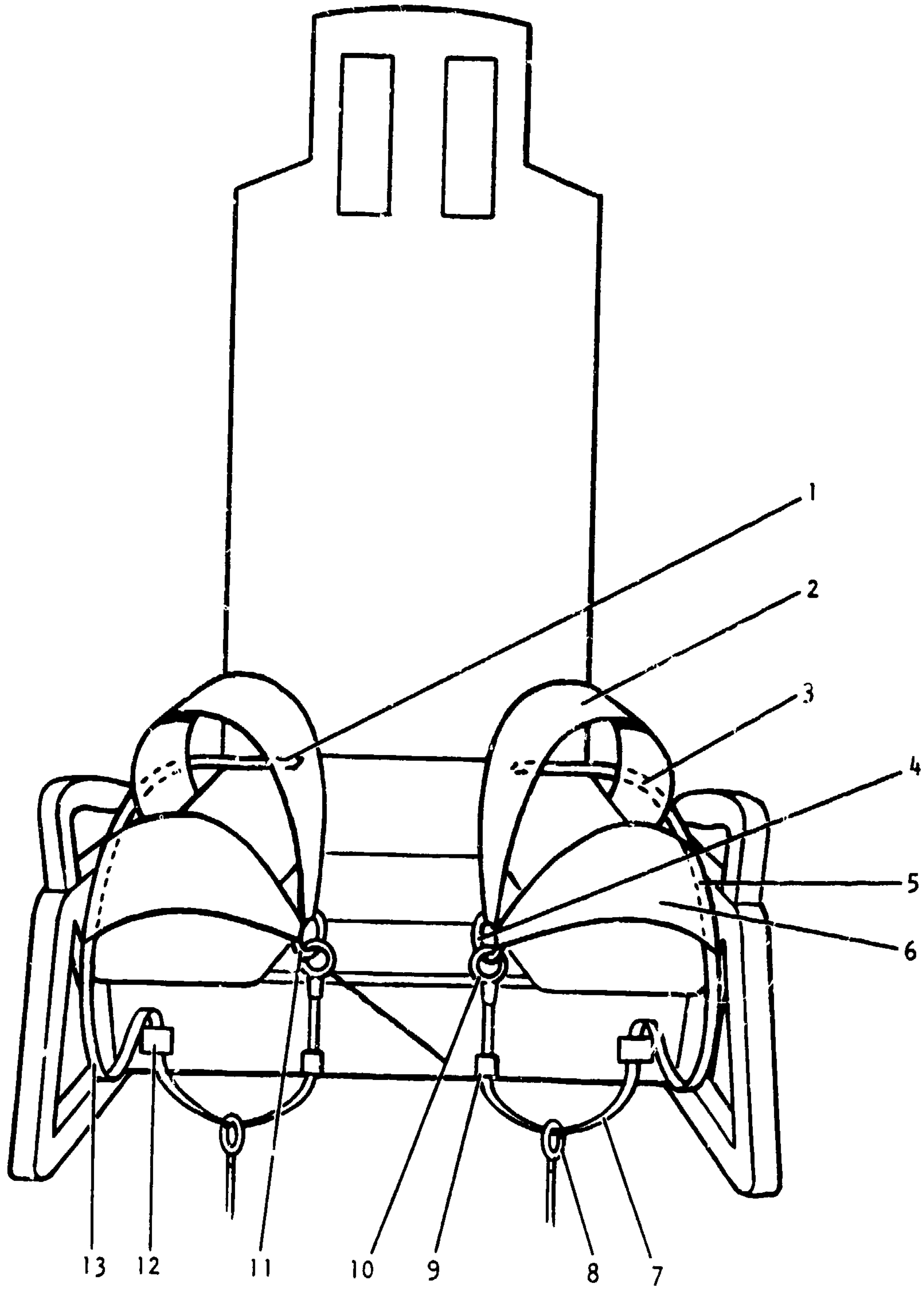


Figure 10. Restraint Concept Number Four.

sewn high on the outer surface of the upper-leg-flap (3). This snugs the upper-leg-flap (2) over the upper leg.

f. At seat-man separation, the snubber/cutter (9) cuts the tensioning strap. This allows the flap-anchor-ring (11) to pull the snap hook (10) away from the snubber/cutter (9), thereby tensioning the sleeve between the snap hook (10) and snubber/cutter (9), which releases the snap-hook-barrel connector (10). This frees the leg-restraint-flaps which are drawn over the legs as the seat falls away from the occupant.

g. At emergency egress, the occupant raises his upper leg against the upper-leg-flap (2). This pulls the flap-anchor-ring (11) and the snap hook (10) away from the snubber/cutter (9). This tensions the snap-hook-barrel-connector-sleeve and releases the barrel connector. The leg-restraint-flaps are then free to slide off the legs during egress.

CONCEPT FIVE

This concept is a leg restraint concept which is very similar to concept four with the exception that it is integrated into the anti-g garment and as such, does not "stay" in the aircraft. It is believed by the authors that careful design of this system could result in its being a straight forward modification of existing anti-g garments, possibly modified at the squadron level. The following deployment sequence references Figure 11.

a. The seat occupant dons a modified g-suit garment which is fitted with leg restraint devices (2 and 6, see insert box) on the upper and lower leg pressure bladders (1 and 5).

b. During the catapult stroke, the retracting-strap (8), which is attached to the floor of the cockpit, is pulled through the snubber/cutter (7) and the center-ring (11) until the mobility-slack-loop (10) is consumed.

c. The retracting-strap (10) tensions against the barrel disconnect (9) and the leg-strap-ring (12), until the leg-strap-ring support loop (3) is forced open. The leg-strap-ring (12) then pulls the leg-strap (4) to and through the center-ring (11).

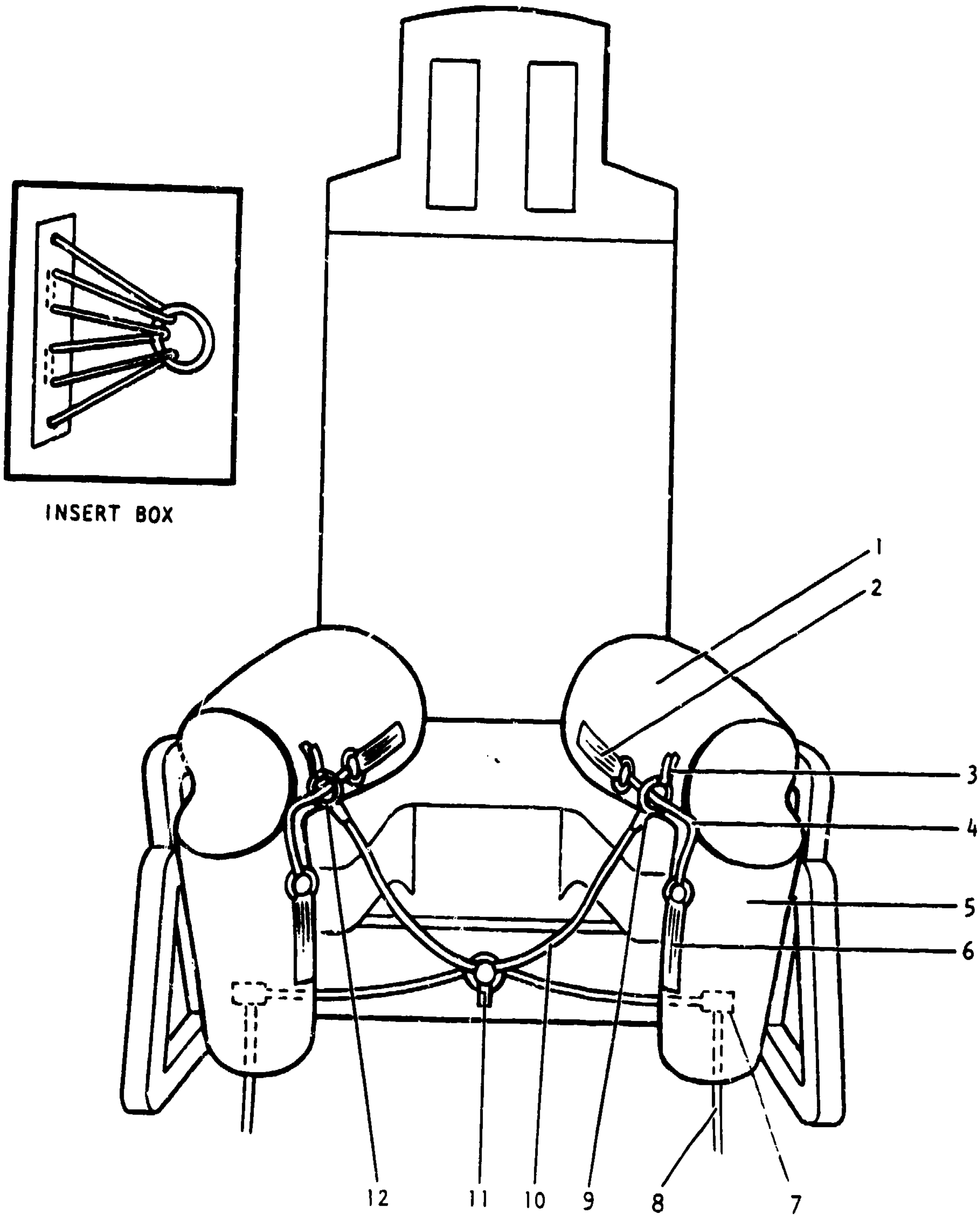


Figure 11. Restraint Concept Number Five.

d. As the leg-strap (4) is drawn through the center-ring (11), the upper and lower leg restraint devices (2 and 6, see insert box) are pulled from their respective keepers and tensioned against the upper and lower legs.

e. The leg restraint devices (2 and 6) pull the upper and lower legs toward the center ring (11) until the barrel disconnect (9) bottoms against the snubber/cutter (7).

f. At seat-man separation the snubber/cutter (7) cuts the restraint strap (10), and the center-ring (11) is mechanically released from its attachment to the seat. The seat is then free to fall away from the occupant.

g. During emergency egress, the leg-strap-ring support loop (3) pulls the leg-strap-ring (12) and barrel disconnect (9) away from the center-ring (11). This tensions the sleeve between the center-ring (11) and the barrel disconnect (9), which, in turn, causes the barrel disconnect (9) to release the leg-strap-ring (12). The occupant is then free to egress from the seat.

CONCEPT SIX

This leg restraint concept is based on the current in-service design on the HS-1 ejection system as used on the RA5-C, reference 13. Discussions with the manufacture indicated, other than some bruises on the shins, no known leg or back injuries have resulted with this system. Twenty-three percent of the documented ejections using this design have been over 500 kts. This system requires elevation of the knees prior to catapult initiation. Although this position looks potentially dangerous for spinal positioning, reference 14 recommends it to increase spinal safety, based on improved spinal alignment as demonstrated by radiological investigations. Lack of back injuries with the HS-1 system reinforces this position. Figure 12 illustrates the original configuration as used in the HS-1 system. Deployment of the system as designed is described in the following text from reference 13.

> "Leg positioning and restraint are accomplished by lifting the knees and locking the feet in foot wells as shown in Figure 12. The knee-raising bar contacts the legs behind the knees. As the knees are lifted, the feet fall into foot wells, and the wells are closed by hooks. If the airman is experiencing acceleration loads, such that the feet will not fall into the foot wells, the hooks contact the lower legs and push the feet into the wells. The system will operate under loads up to 12 g's.

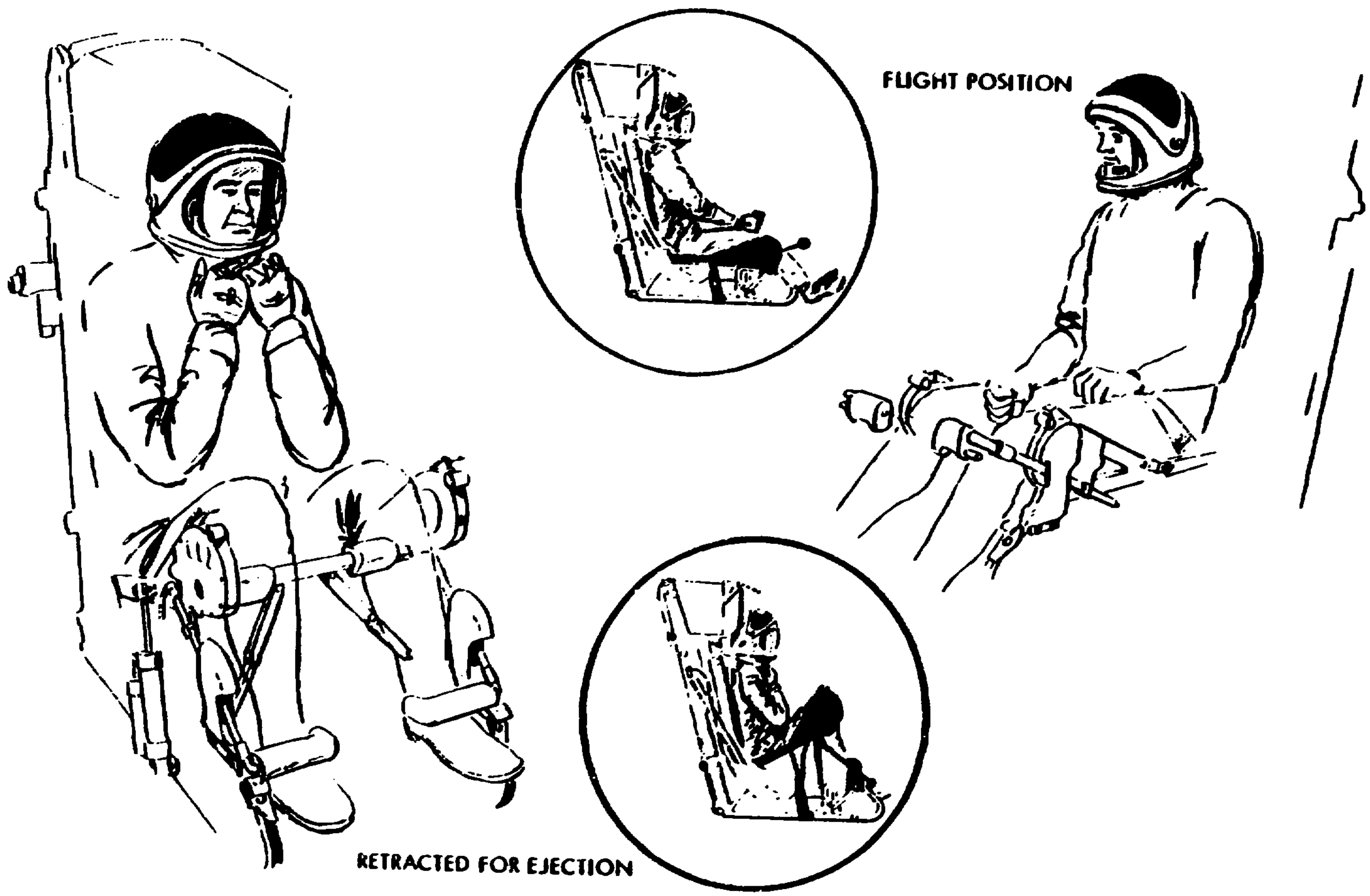


Figure 12. Restraint Concept Number Six, Original Configuration.

The pivot points of the knee-raising bar arms are below and aft of the pivot points of the hips. This ensures no submarining (forward movement of the lower torso) from the leg positioning action; should the airman's lower torso not be properly positioned due to improper harness adjustment, the leg positioning actually positions his lower torso.

The forces imposed on the man by the leg positioning procedure are insignificant. The knee-raising bar has a maximum velocity of 5.3 ft/sec, and the hooks have a maximum velocity of 9 ft/sec. All have energy absorption pads where they contact the legs."

Modifications proposed for the system are not intended to change the functional characteristics, but allow it to be more readily adaptable to existing ejection seats and installations. The baseline modification is shown on Figure 13.

CONCEPT EVALUATION

CONCEPT DESIGN STUDIES

A design study should be performed on each of the six arm and leg restraint concepts presented in Figures 7 through 13. The aim of these studies should be the determination of the dimensional configuration, the strength requirements and general materials requirements for each concept. Human subjects and full-scale soft mock-ups of each concept should be used for these determinations. The results of these studies should be documented in a layout drawing for each concept.

CONCEPT PROTOTYPES

Subsequent to the design studies, a testable prototype of each concept should be constructed. These prototypes should serve as development tools as well as vehicles for preliminary performance evaluation. Therefore, the detail design of these prototypes should emphasize configuration flexibility as opposed to fidelity to flyable hardware. The prototypes should be suitable for testing with human subjects. Therefore, the prototype designs should also emphasize subject safety during testing. At a minimum, the prototypes should be capable of sustaining 4 g equivalent loading in any direction. The prototype should be designed for rapid installation on and removal from an ejection seat test fixture.

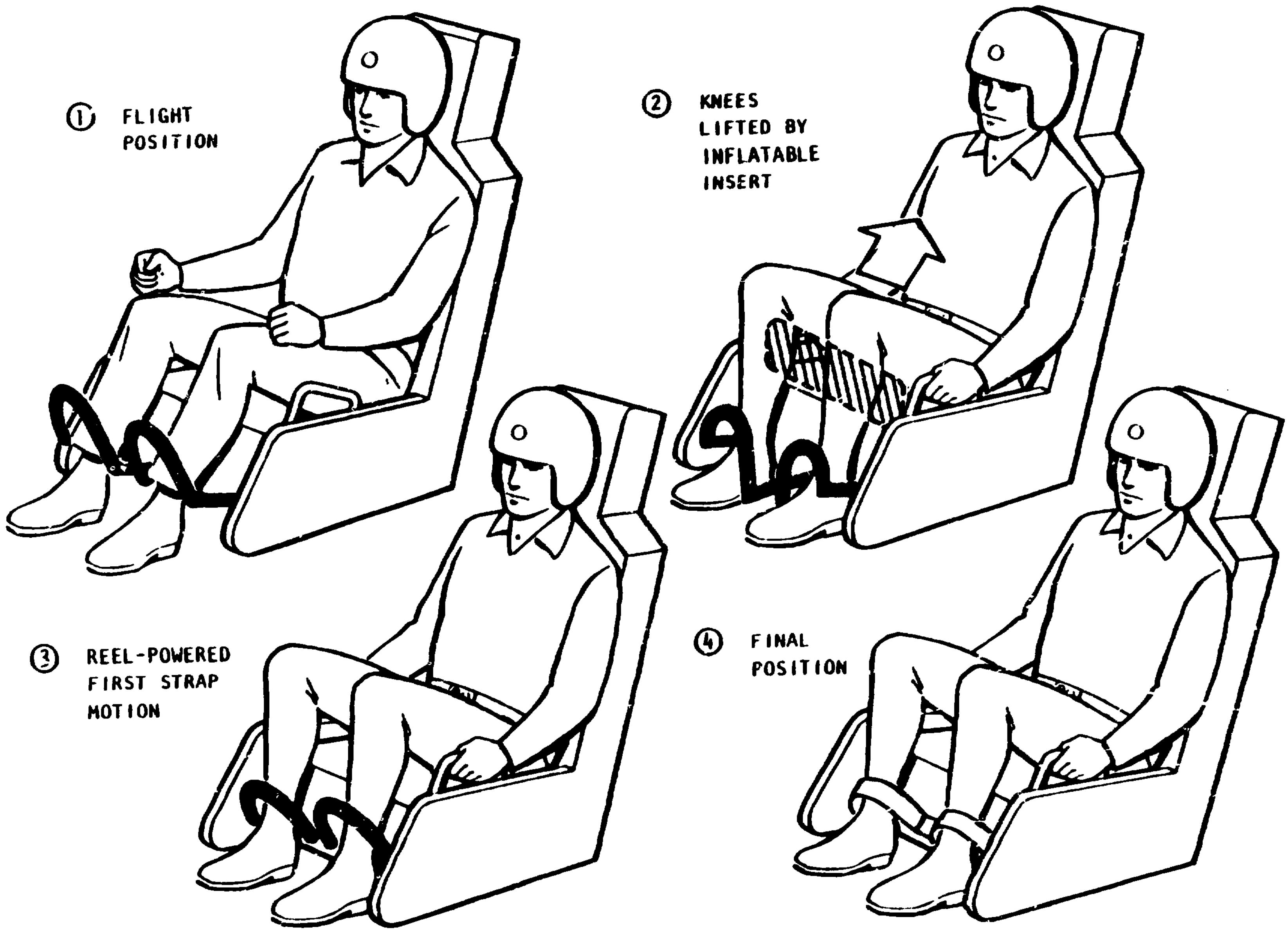


Figure 13. Restraint Concept Number Six, Proposed Modification.

LOW FORCE TEST FIXTURES

A set of low force test fixtures should be used for preliminary evaluation of the concept prototypes. These fixtures should include a seat, a cockpit mock-up, a pitch/roll seat positioning apparatus, a device for simulating powered restraint deployment, a fixture capable of simulating seat-occupant response to the drogue snatch event on a yawed seat, a fixture capable of simulating the free flight dynamics of seat-man separation, and a device for simulating the effects of windblast on restraint deployment. These fixtures need not possess high structural strength, since the preliminary evaluations to be performed on them should be conducted at low force levels, that is, less than 4 g equivalent force.

Seat Fixture

The seat fixture should be an actual ejection seat shell, preferably an ACES II. The seat should have an operable primary restraint release system, including the manual release control handle, and a pneumatically powered inertia reel or other device capable of simulating powered upper torso retraction. The seat should be modified to receive each of the six restraint concept prototypes. These modifications should include simulations of any restraint release devices required by the concept designs.

Cockpit Fixture

The cockpit fixture should provide the spatial configuration of a typical fighter cockpit. It should accept installation of the seat fixture and should be suitable for use in ingress, egress, donning, doffing, and emergency egress demonstrations.

Pitch/Roll Positioning Fixture

The seat positioning fixture should be capable of positioning the seat and a human occupant in all possible attitudes in relation to the gravity vector. Sufficient space should be provided around the seat to allow unobstructed movement of the occupant's limbs. The fixture should be used to study the interaction of the occupant's body with the restraints while the direction of action of the simulated ejection forces, i.e., gravity, is changed. Specifically, the fixture should facilitate the characterization of limb joint loading processes which result from such interactions.

Powered Deployment Simulator

A device capable of simulating powered retraction of restraint deployment straps should be available. The device should have the capacity to independently retract four different straps. The power and speed of retraction should be variable. The device should be compatible with seat installation in either the positioning fixture or cockpit fixture.

Drogue Snatch Fixture

A simple and sufficient drogue-snatch simulator could employ a falling weight to give the seat and its occupant, at a 90-degree pitch angle, a vertical velocity which could then be arrested by simulated drogue risers attached to the ground. The main component of a fixture using this approach would be a platform upon which the seat would be mounted facing upward. The platform would be suspended from the drop-weight cable by two pulley-cable sets which would allow the platform to rotate on the seat's yaw axis. If the pulley-cable sets were mounted at the ends of a horizontal beam which was suspended at its center by the drop-weight cable, the platform would also be able to rotate about the seat's pitch and roll axes. The upward facing orientation of the seat permits exploiting the gravity vector to simulate the inertial push of the seat against the occupant. If the platform suspension cables are mounted asymmetrically with respect to the seat-platform CG, the platform can be made to yaw accelerate as it is accelerated vertically by the falling drop-weight. Therefore, the fixture would be capable of simulating yaw velocity reversal at drogue-snatch.

This fixture should be used to study the dynamic response of the seat and occupant to the drogue snatch event. In particular, the fixture should be used to study the response of the limbs and limb restraints to seat realignment at drogue-snatch.

Seat/Man Separation Simulation

Seat/man separation simulation should be accomplished by dropping an occupied seat through some distance before catching the occupant by his parachute risers. The facility for conducting these simulations should provide for arresting the seat to avoid damage at ground impact. The drop release device should be capable of imparting angular rates to the seat prior to seat/man separation. This facility should be used to study the behavior of limb-restraint devices during unstable seat/man separation.

Windblast Simulator

A large six to eight foot diameter fan of the type used for commercial movie productions would be sufficient for preliminary evaluation of the response of the prototype limb restraints to windblast during deployment. If necessary, a large duct should be designed and constructed to remove the radial and cyclonic flow properties from the fan's output and to direct the output airflow at the seat.

PROTOTYPE EVALUATIONS

The necessary performance evaluations are listed in Table 8. The table also identifies the test fixtures or facilities required by each of the evaluations. Whenever safety requirements permit, human subjects should be employed in these evaluation demonstrations. Otherwise, fully articulated anthropometric dummies should be used.

Biomechanical Loading Evaluations

Each concept's performance regarding the forces, torques, tensions, compressions, and shear loads which are induced in the occupant's limb segments and joints should be evaluated. Such forces can result from restraint system deployment and cinching, and from the mechanisms by which the restraints react the aerodynamic and inertial forces operating on the seat and occupant during seat deceleration and stabilization. The torso reaction, restraint deployment, drogue snatch, and seat-man separation simulators should be used to assess each concept's biomechanical loading performance during those events. The seat positioning fixture should be used to assess the general interaction between the restraints and the occupant's body for all loading directions.

Deployment Failure Modes

The deployment phase of each concept prototype's operation should be evaluated for the possible existence of deployment failure modes. To this end, simulated restraint deployments should be made with the seat installed in the cockpit simulator, with seat exposed to airflow from the windblast simulator, and with the seat held at adverse attitudes with respect to gravity by the seat positioning fixture.

Seat-Man Separation Failure Modes

The release phase of each concept prototype's operation should be evaluated for the possible existence of release failure modes. To this end, the seat-man separation simulator should be used to investigate the behavior

TABLE 8 . EVALUATION AREAS FOR LIMB RESTRAINT CONCEPTS AND RELATED TEST FIXTURES AND SIMULATORS

FIELD SIMULATORS / EVALUATIONS	SEAT	TORSO RETRACTION SIMULATOR	COCKPIT SIMULATOR	SEAT POSITIONING	RESTRAINT DEPLOYMENT SIMULATOR	DROGUE SNATCH SIMULATOR	SEAT-MAN SEPARATION SIMULATOR	WINDBLAST SIMULATOR
Biomechanical Loading	X	X		X	X	X	X	
Deployment Failure Modes	X		X	X	X			X
Seat/Man Separation Failures Modes	X			X			X	
Adverse Limb/Torso Position Failure Modes	X	X	X		X			
Mobility in Primary Restraints	X			X		X		
Anthropometry Sensitivity	X		X	X				
Post-Separation Entanglement	X		X				X	
Manual Separation Control Access	X							
Psychological Acceptibility of Encumberance and Appearance	X		X	X				
Donning and Doffing Procedures	X		X					
Personal Protective Equipment	X		X	X				

of the prototypes under various dynamic conditions at seat-man separation. Slow motion photography and force measuring instrumentation should be used to record the detailed behavior of the restraints as they are pulled off the limbs during separation.

Adverse Limb/Torso Position Failure Modes

A subset of potential deployment failure modes are those attributable to adverse limb and/or torso positions prior to initiation. The torso retraction and restraint deployment simulators should be used to investigate the possible existence of such failure modes. With the seat installed in the cockpit simulator, the limbs and torso of human subjects should be placed in various adverse positions prior to concurrent simulations of torso retraction and restraint deployment. Under these conditions, the pre-ejection limb positioning performance of the concept prototypes, as well as the probability and significance of any observed failure modes, should be evaluated.

Mobility in Primary Restraints

Since a reduction of the range of occupant mobility within the cinched primary restraints, caused by restraint of the limbs, may result in the transfer of some of the torso loads, normally reacted by the primary restraints, through the limbs to the limb restraints, each concept prototype should be evaluated for any potential reductions of occupant mobility within the primary restraints. The seat positioning fixture should be used to simulate various loading directions between the seat and occupant so that potential limb restraint restrictions on occupant mobility may be observed and evaluated. Any potentially hazardous mobility restrictions observed on the seat positioning fixture should be further evaluated by observing and comparing the dynamic behavior of the seat and occupant, with and without limb restraints, generated by the drogue snatch simulator.

Anthropometry Sensitivity

The performance of a limb restraint concept during all of its phases of operation should be uneffected by occupant anthropometry. A special evaluation of each concept prototype for potential anthropometry sensitivities should be performed using the seat installed in the cockpit simulator and seat positioning fixture. Any potentially hazardous sensitivities should be further observed and evaluated during testing of the concept prototypes on the various dynamic simulators.

Post-Separation Entanglement

After seat-man separation, limb restraint system components which stay with the occupant may represent entanglement hazards during ground or water landings, or emergency egress. Concept prototype tests in the cockpit and seat-man separation simulators should be monitored with the aim of detecting any potentially hazardous entanglement situations.

Manual Separation Control Access

Manual access to the emergency seat-man separation control handle, in the event of primary restraint release failure, is highly desirable. Each concept prototype's performance on this desired capability should be evaluated first by deploying the prototype around a human occupant, then verifying that he has access to and can operate the control. Then a more realistic evaluation should be performed by first suspending the restrained occupant, while in the seat, from simulated parachute risers attached to the occupant's harness. The occupant should attempt to access and operate the control in this situation. If the attempt is successful, the seat should be allowed to drop away from the occupant so that the release and shedding of the limb restraints under 1 g conditions may be observed.

Psychological Acceptability of Encumbrance and Appearance

If a design concept ultimately depends on the voluntary cooperation of the seat occupant for its successful operation, then the using population's psychological acceptance of the concept in regard to encumbrance and appearance may play a large part in determining the concept's potential long-term effectiveness. The first step in evaluating a concept's potential acceptability should be to evaluate its performance regarding encumbrances. This should be accomplished by using the cockpit simulator and seat position fixture along with human subjects to assess each concept's prototype's impact on reach and vision access in the cockpit, as well as prototype's responses to off-vertical acceleration loads, such as would be encountered in high-speed maneuvering. If these studies indicate that a concept should be acceptable with regard to encumbrance, the concept design should be reviewed for acceptable appearance. A simple, rugged appearance is desirable. Improvements in appearance should be allowed to influence material selection, and keepers and other devices for giving a simple external appearance should be used wherever possible. After these preliminary assessments are completed, members of the flying population should be invited to study the concept prototypes and give their assessments regarding the prototype's encumbrance and appearance.

Donning and Doffing Procedures

The donning and doffing procedures required by each design concept should be evaluated by collecting information on the number of tasks in each procedure, on the average time taken for each task, and on the difficulty of each task. A special effort should be made to identify tasks which may often take two or more attempts to successfully complete or which may present other special difficulties to the seat occupant. The cockpit simulator should be used to demonstrate the compatibility of donning and doffing procedures with cockpit geometry. Human subjects representing the 5th and 95th percentile anthropometric sizes and wearing winter and summer personal equipment should be employed to evaluate the sensitivity of the procedures to these variables. The capability of each concept prototype to automatically accommodate changes in occupant size and personal equipment bulk should also be evaluated.

Personal Protective Equipment

Since the occupant's personal protective equipment usually occupies the interface between the limb restraint devices and the occupant's body, subjects should wear government issued personal equipment at least once for each of the evaluation demonstrations. The pencil pockets on the sleeves of the flight suit or flight jacket are critical, because the pencils or pens they carry represent potential snags for some deploying arm restraint designs.

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